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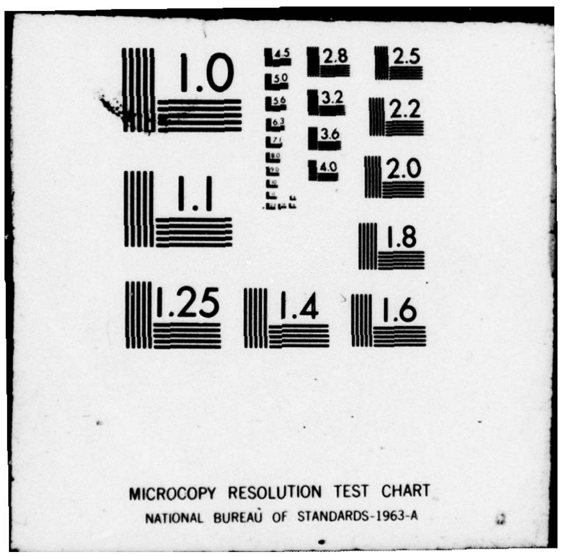
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PROJECT SQUID.

SEMI-ANNUAL PROGRESS REPORT

1 APRIL 1979

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West Lafayette, Indiana 47907

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SEMI-ANNUAL PROGRESS REPORT

PROJECT SQUID

A COOPERATIVE PROGRAM OF FUNDAMENTAL RESEARCH
RELATED TO JET PROPULSION
OFFICE OF NAVAL RESEARCH, DEPARTMENT OF THE NAVY

THIS REPORT COVERS THE WORK ACCOMPLISHED
DURING THE PERIOD 1 OCTOBER 1978 TO MARCH 31, 1979
BY PRIME AND SUBCONTRACTORS UNDER
CONTRACT N00014-75-C-1143, NR-098-038

1 APRIL 1979

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I. AERODYNAMICS AND TURBOMACHINERY

Semi-Annual Progress Report

THREE DIMENSIONAL TRANSONIC FLOWS IN COMPRESSORS AND CHANNELS

The University of Michigan, Ann Arbor, Michigan
Subcontract No. 8960-10

Professor T.C. Adamson, Jr., Principal Investigator
Professor M. Sichel, Principal Investigator

Introduction

This research project is concerned with the use of asymptotic methods of analysis in the study of transonic flow through a compressor blade row. The mixed flow problem, where the incoming flow relative to the blades consists of a supersonic region exterior to and a subsonic region interior to a sonic cylinder is of special interest. The problem of the three dimensional rotor flow has been formulated and first order solutions valid in the channel-like region between the blades have been found. Recently attention has been focused on obtaining solutions in the region upstream of the blades.

Discussion

It is convenient, in describing the flow through a rotor, to consider the cascade flow picture associated with the flow on any constant radius cylinder. In terms of coordinates aligned along and perpendicular to the incoming flow relative to the blades, in such a cascade, it is clear that the flow consists of a mixture of flow through a channel and

flow over an individual airfoil. The extent of the channel flow, where the channel walls consist of part of the surfaces of two successive blades, depends on the stagger angle of the cascade at the radial position in question. Within this channel like region, if the blade thickness is $O(\epsilon^2)$, then variations of $O(\epsilon)$ are found in the velocity component in the relative incoming flow direction, U. However, in the region upstream of the channel flow region, where the flow behaves more as it would over a single airfoil, it has been found that variations in U induced by the blades are only $O(\epsilon^{3/2})$. This implies that if one wishes to write a solution which shows flow variations both upstream of and within a compressor rotor, it is not sufficient to employ a perturbation solution which involves only one order of approximation. The flow perturbations induced upstream of the rotor, in both supersonic and subsonic flow cases, are of higher order (i.e., smaller) than those induced in the channel like flow region between the blades.

Because the above mentioned result is new, it was decided to investigate it thoroughly for the simpler two dimensional cascade geometry. Accordingly, two studies have been made, one for subsonic and one for supersonic incoming flow, using asymptotic techniques. Analytical solutions exhibiting the different order perturbations in the upstream and between blade flow regions have been found for both the supersonic and subsonic incoming flow cases. In the latter case, both sharp and rounded leading edges are being considered. An important result of this analysis is that because of the change in order of the perturbations in flow velocities, it is never necessary to consider the small disturbance nonlinear equation for transonic flow. Before the Mach number of the incoming flow becomes small enough to cause nonlinear effects to become important, the flow chokes in the channels between the blades. This is, of course, a result which has only been demonstrated for two dimensional flows. However, it appears that it may be true for the three dimensional flow case also.

An additional feature of the solutions is relatively simple identification of the so-called unique incidence angle associated with the incoming flow for the two dimensional cascade. An interesting point of study will be to ascertain whether this concept is valid in the three dimensional rotor flow case as well.

The two dimensional cascade flow solutions will be completed soon and then reported in detail.

AXIAL FLOW FAN STAGE UNSTEADY PERFORMANCE

Applied Research Laboratory
The Pennsylvania State University
P. O. Box 30, State College, Pennsylvania 16801

Subcontract No. 8960-4

Edgar P. Bruce, Principal Investigator

Introduction

The objective of this research is to analyze the time-dependent interaction between the components of an isolated axial flow fan stage and a spatially fixed, circumferentially varying flow field. The major variables are reduced frequency; rotor blade space-to-chord ratio, stagger angle, mean angle of attack, and design loading level; and rotor-stator axial spacing.

The experiments are being conducted in the ARL Axial Flow Research Fan. This facility has a hub radius of 12.06 cm (4.75 inches), a hub-to-tip radius ratio of 0.442, and operates in the subsonic incompressible flow regime. The rotor and stator blades have a 10 percent thick C1 profile with a chord of 15.24 cm (6.00 inches) and an aspect ratio of unity.

Instrumentation available at present or under development consists of: (1) a strain gaged sensor mounted within one rotor blade which detects the time-dependent normal force and pitching moment developed on a mid-span blade segment, (2) hot-film sensors mounted on the suction surface of rotor and stator blades which detect the nature of the boundary layer, i.e., whether the instantaneous boundary layer flow is laminar, turbulent or separated; (3) dynamic total head probes; (4) two-element hot-film probes; and (5) conventional three-dimensional directional probes. A system is being developed which will permit on-line analysis of all time-dependent signals by a digitizing, phase-lock averaging process.

The unsteady normal force and pitching moment results obtained in the initial phase of this program at reduced frequencies from 0.2 to 2.1 have been documented in a Project SQUID report (Reference 1). Since completing the initial phase, our efforts have been directed toward extending the reduced frequency range of the uncambered rotor experiments (Reference 1) from 2.1 to 5.0, and toward a detailed examination of the effects of inflow distortion on the performance of a stage designed with a free-vortex loading distribution. A related theoretical effort has as its goal an extension of the unsteady lift cascade model developed by Henderson (Reference 2) to include the unsteady pitching moment.

Discussion

During this reporting period, we have made progress in both the experimental and theoretical areas. With respect to the experimental tasks, we have.

(1) Employed the "Galton Whistle" standing wave tube to dynamically calibrate a total pressure probe. This probe consists of a miniature piezoresistive pressure transducer mounted in the body of a commercially available Kiel probe.

(2) Employed an open jet calibration facility to statically calibrate a Kiel probe for use with the dynamic Kiel probe. Use of this combination of probes permits obtaining both the steady and unsteady components of the total pressure.

(3) Initiated the check-out effort necessary to employ a newly acquired SD 134A Tracking Ratio Tuner in our data analysis system. Use of this tuner provides the capability to phase-lock average and analyze time-dependent signals using an SD 360 Digital Signal Processor with an external trigger pulse.

The theoretical effort has been devoted to development of an expression for the unsteady pitching moment using the cascade vortex model employed by Henderson (Reference 2) in his derivation of an expression for unsteady cascade lift. Programming of the solution for the unsteady pitching moment about an axis through the blade mid-chord position on the IBM 360 is underway at present and should be completed in the near future. A report summarizing the results of this effort is also nearing completion.

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1. Bruce, E. P. and Henderson, R. E., "Axial Flow Rotor Unsteady Response to Circumferential Inflow Distortions," Project SQUID Technical Report PSU-13-P, September 1975.

2. Henderson, R. E., "The Unsteady Response of an Axial Flow Turbomachine to an Upstream Disturbance," Ph.D. Dissertation, Engineering Department, University of Cambridge, 1972.

INVESTIGATION OF THE EFFECTS OF HIGH AERODYNAMIC LOADING ON A CASCADE OF OSCILLATING AIRFOILS

United Technologies Research Center
East Hartford, Conn. 06108
Subcontract 8960-19

Franklin O. Carta, Principal Investigator
Arthur O. St. Hilaire, Principal Investigator

Introduction

The basic objective of this research program is to study the effect of aerodynamic loading on a cascade of oscillating airfoils. Unsteady pressure time histories have been obtained both along the chord of the cascade center blade and along the inlet and exit planes of the blade row. Data acquisition was achieved for mean incidence angles up to α_{mcl} = 10 deg, reduced frequencies up to k = 0.193, an interblade phase angle range of σ = -60 deg, to + 60 deg, and a series of gap-to-chord ratios: τ = 0.75, 1.50, and 2.25. These data are now being used to calculate the stability parameters of the system including the unsteady pitching, moment coefficient and the aerodynamic damping parameter. A preliminary effort is also being initiated to study the individual leading edge region pressure time histories in detail with the purpose of determining how the leading edge region load behavior affects the stability of the cascade pitching motion.

Program Review

The experimental program has been completed, thus providing a comprehensive picture of the effects of all parameters on cascade stability. With the exception of gap-to-chord ratio effects, the main results of the test program have been partly summarized in a paper being presented at the 1979 International Gas Turbine Conference in San Diego (Ref. 1). For the range of parameters tested it was found that the interblade phase angle is the most important parameter affecting cascade stability. Specifically, for the entire range of loading and reduced frequency tested, it was found that the cascade is stable at negative σ while generally unstable at most positive values of σ. It was also found that the stability parameters were more sensitive to loading and frequency at negative σ than at positive σ. In particular, for $\sigma < 0$, the stability margin increases with frequency and decreases with increasing load.

The leading edge region pressure time histories for the entire range of loading and reduced frequency have been qualitatively and quantitatively examined. In particular, the sensitivity of the pressure data to variations in reduced frequency and interblade phase angle was examined at three different loadings and the primary trends were identified. For all loadings and frequencies tested the behavior of the response very near the leading edge was found to be narrowly confined as the events displayed there are mostly absent from the time histories at the 6.2 percent chord station. It was further determined that at moderate (α_{mcl} = 8 deg) to high (α_{mcl} = 10 deg) loads, the response at the 1.2 percent chord station has almost no influence on cascade stability. As a result, the response at the 6.2 percent location dominates the component of the aerodynamic response that affects cascade stability. It was also found that the functional dependence of the response on σ is largely independent of the mean incidence angle in that for all cases tested the unsteady response generally shifts from lagging (stable) to leading (unstable) the blade motion as σ varies from negative to positive values.

A preliminary analysis is presented in an attempt to describe a possible mechanism through which σ might influence the stability of the cascade motion. The concept of a σ-dependent periodic inlet is introduced and a simple geometry (which is generally unrelated to the cascade system) is chosen to illustrate the analytical procedure which couples the motion of the inlet to the surrounding flow field. Results show that such a coupling will induce an instability for $\sigma > 0$. A more representative model is planned.

A report of this preliminary effort is being prepared.

Reference

1. Carta, F. O. and St. Hilaire, A. O., "Effect of Interblade Phase Angle and Incidence Angle on Cascade Pitching Stability", ASME Paper 79-GT-153 Gas Turbine Conf., San Diego, CA, 1979.

INVESTIGATION OF ADVERSE PRESSURE GRADIENT CORNER FLOWS

University of Washington, Seattle, Washington
Subcontract No. 8960-27

Professor F.B. Gessner, Principal Investigator
Mr. Y.L. Chan, Research Assistant
Mr. S.A. Arterberry, Research Assistant

Introduction

The flow along a streamwise corner formed by two intersecting surfaces is sensitive to an imposed adverse pressure gradient. With reference to flow in a rectangular diffuser, for example, the flow can separate locally in the vicinity of a corner while remaining attached elsewhere. Even if the flow remains wholly attached, flow in the corner region is most susceptible to departures from near equilibrium, so that predictive methods based on local equilibrium concepts may not be adequate. Furthermore, empirical wall functions which are commonly used to replace wall-specified boundary conditions may no longer be applicable, and therefore not only the turbulence model but also the specified boundary conditions must be modified in order to predict the local flow structure accurately. This study was initiated in order to provide insight into the influence of adverse pressure gradients on local corner flow behavior. For this purpose a rectangular diffuser used in a previous study [1] has been modified to facilitate measurements in the corner region for various imposed adverse pressure gradients. The initial phase of the work consists of making both mean flow and turbulence measurements for wholly attached flow in the diffuser up to incipient separation in the corner region. The data will be analyzed from the standpoint of determining the limitations of current local equilibrium turbulence models or, alternatively, the conditions under which non-equilibrium effects must be taken into account. The second phase of the program will include additional flow visualization studies in order to develop a physical picture of corner flow separation. The development of a criterion for incipient separation at a corner will also be included in this phase of the work.

Discussion

In order to implement the objectives of this study, a separate hot-wire response study was conducted for the purpose of developing a technique for

making Reynolds stress measurements in the presence of a three-dimensional, highly skewed mean flow. The results of this study are described in a recent thesis [2] and were presented last year at the Symposium on Dynamic Measurements in Unsteady Flows [3]. Revisions to the rectangular diffuser flow facility have now been completed and include the following modifications: A precision inclinometer has been constructed which can be used to set the divergence angle of either diverging wall of the diffuser to within ±0.05 degrees. Static pressure taps (48) have been added to the bounding walls of one corner in order to measure streamwise and transverse wall static pressure variations more adequately. The static pressure data will be used in conjunction with Preston tube data to determine local wall shear stress values. This technique is subject, of course, to the existence of a well-defined log-law region at each measurement location. On the basis of recent corner flow measurements made in our laboratory, this condition should be valid for operating conditions not near incipient separation.

The bounding walls adjacent to another corner of the diffuser now include an array of wool tufts. Preliminary observations have indicated that intermittent transitory stall exists in the vicinity of a corner when the total diffuser divergence angle is approximately 10 degrees. Initial measurements of the local flow structure will be restricted to divergence angles less than or equal to 8 degrees, therefore, which corresponds to wholly attached flow in the diffuser. In addition to the above modifications, a traveling microscope has been mounted on a two-axis traverse outside the diffuser which can be used to view an edge of a diverging wall in contact with either Plexiglass side wall. This arrangement will be used to determine the coordinates of the curved section which joins the planar upstream (parallel) and downstream sections of each diverging wall. This information, in turn, will facilitate comparisons between predicted and measured results, because the diverging wall contour will be completely specified between the upstream location where inlet flow data are being taken and the last downstream station.

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1. Fiedler, R.A., and Gessner, F.B., "Influence of Tangential Fluid Injection on the Performance of Two-Dimensional Diffusers," Journal of Basic Engineering, Trans. ASME, Series D, Vol. 94, No. 3, 1972, pp. 666-674.

2. Littlefield, M.T., "Investigation of Hot-Wire Response Characteristics in Skewed Mean Flow," M.S. Thesis, Department of Mechanical Engineering, University of Washington, 1978.

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SQUID PR-5

TRANSITORY STALL IN DIFFUSERS

Thermosciences Division
Department of Mechanical Engineering
Stanford University
Stanford, California 94305
Subcontract No. 8960-24

Professor James P. Johnston, Principal Investigator
Professor Stephen J. Kline, Principal Investigator
Mr. Jalal Ashjaee, Research Assistant

Introduction

The general goal of this program is to study the transitory stall flow regime in two-dimensional diffusers. Maximum value of pressure recovery at fixed non-dimensional length, an important design optimum [1], generally occurs when the turbulent boundary layers are starting to separate or stall. The flow is rather unsteady and significant amounts of transient back flow already are seen in the diffuser at peak pressure recovery. These flow conditions are associated with the onset and development of the transitory stall flow regime [2].

Ghose and Kline [3] have developed a new, steady flow boundary layer prediction method which is solved simultaneously (not iteratively) with the inviscid core flow. This method gives surprisingly good agreement with data on pressure recovery up to, and slightly beyond the condition of peak recovery. The existing wall pressure data in this region are not of sufficient accuracy to properly check the method, however.

The primary objectives of our program are (i) to provide new mean and fluctuation velocity and pressure data in diffusers operating close to peak pressure recovery in order to complement, check and provide a data base of sufficient accuracy to allow for possible improvement of the prediction method of Ghose and Kline [3], and (ii) to study the magnitude of the velocity and pressure fluctuations in the transitory stall regime in order to provide a useful extension of the work of Smith and Kline [2] and Layne and Smith [4].

Discussion

The diffuser experiments have been concentrated on measurement of flow direction intermittency very near the wall. Denoted by γ_p, intermittency is defined here as the fraction of the time that the flow in the wall layers is in the downstream (forward) direction. Distribution of γ_p along the diffuser walls have been measured for several symmetric diffusers of $L/W_1 = 15$ operating in the neighborhood of peak pressure recovery. The instrument used, the thermal tuft, or wall-flow-direction probe, was developed for this purpose and is completely explained in Ref. [5].

Two typical distributions of γ_p are illustrated in Figs. 1 and 2 for cases of $2\theta = 10$ and 9 degrees, in the vicinity of peak pressure recovery. In Fig. 1, $2\theta = 10°$, results are presented for two separate experimental runs corresponding to the two cases where the stalled region has been established on either side-wall A or on side-wall B. TD (Transitory Detachment) and ITD (Intermittent Transitory Detachment) in this plot, correspond to 50% and 20% reverse flow as defined in Ref. [6]. The dotted lines specified as $H = H_{sep}$ (corresponding to the separation criterion of Sandborn and Kline) and $\overline{C}_f = 0$ are the locations of intermittent and fully developed separation predicted by the modified version of the UIM method. (See SQUID PR-4, September 1978). It is readily observed that the separation phenomenon covers a significant portion of the diffuser's wall, and the locations of intermittent and fully developed separation are widely separated.

Fig. 2 illustrates a phenomenon that has not been observed or documented before. As seen in this figure, the two walls of the diffuser undergo some degree of reverse flow in the same experiment, however, the differences in the γ_p curves show that the process is not symmetric on the two side-walls. Measurements on wall A show only a small amount of backflow is present on this wall, while wall B, on the other hand, is on the verge of detachment. Further experiments on γ_p distributions revealed patterns analogous to those of $2\theta = 10°$ and $9°$ for $2\theta = 12°$ and $8°$ respectively.

Work has also been proceeding in developing a prediction code based on the UIM method, but using a more realistic approach which assumes that the boundary layers on the diffuser walls must be treated separately. Furthermore, changes are made in the relationships between boundary layer integral parameters and in the core model. Other improvements in the method of solution, particularly in the neighborhood of detachment, are underway and will be reported later.

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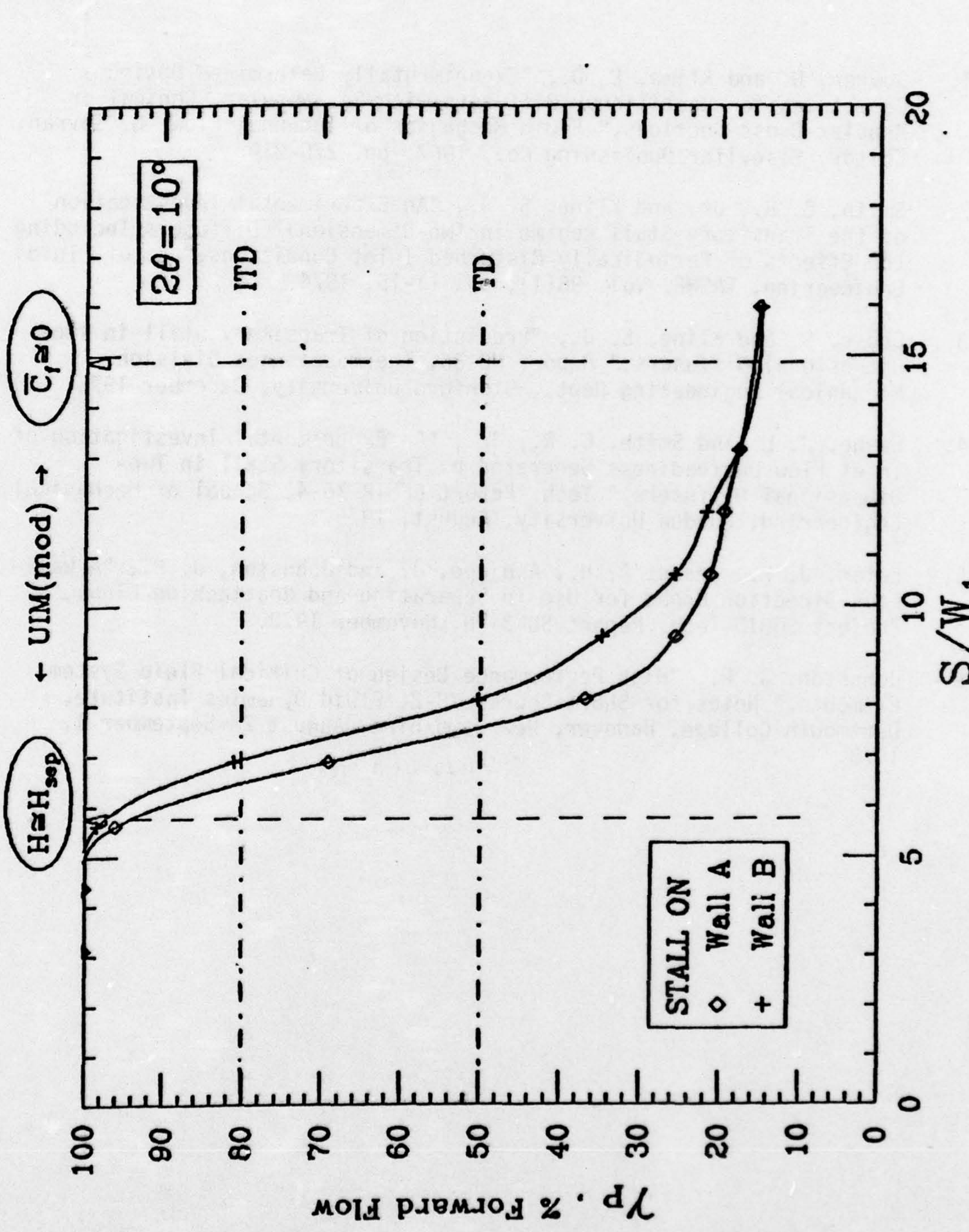
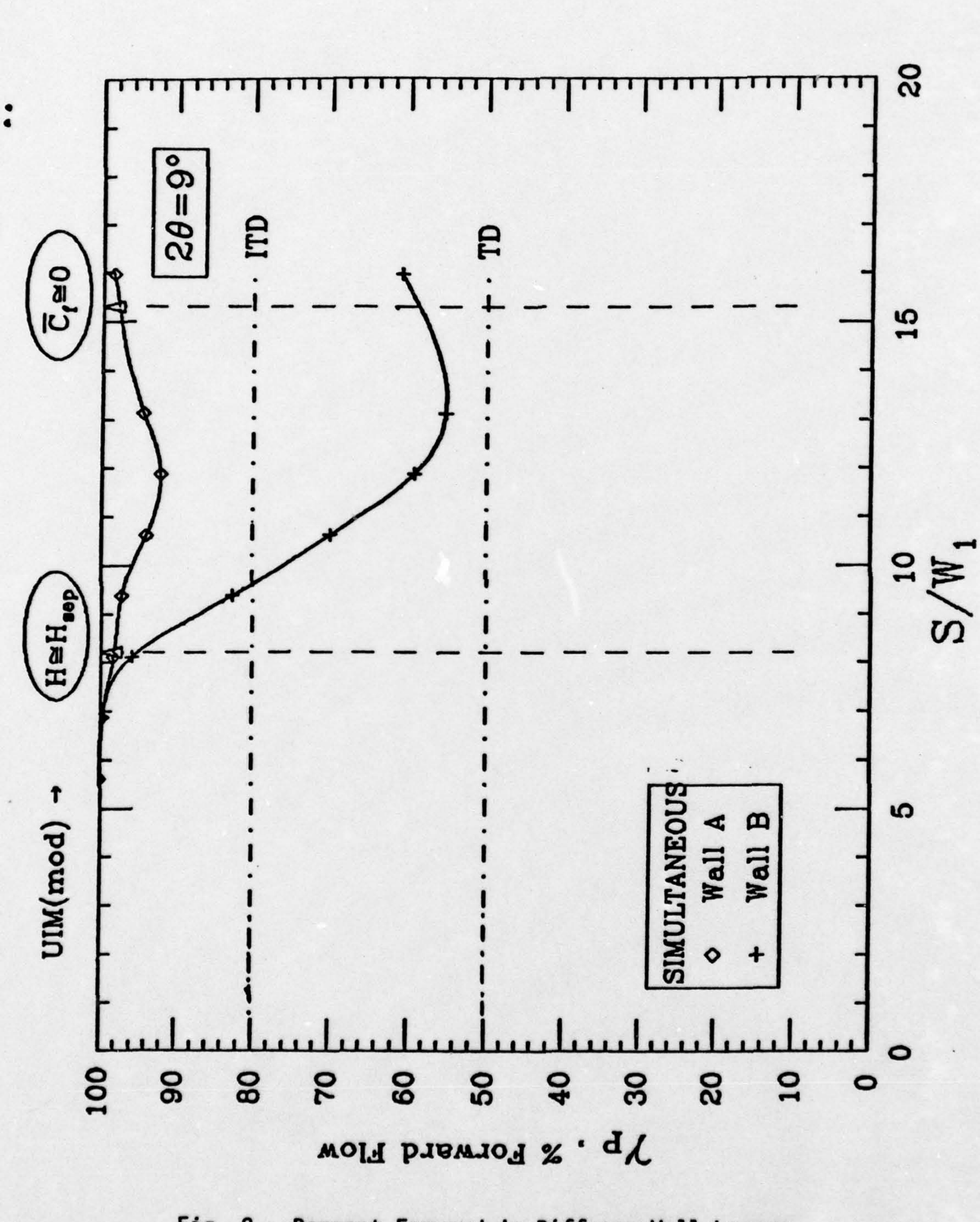


Fig. 1 - Percent Forward Flow in Diffuser Wall Layers Versus Distance Along Diffuser Wall



<u>Fig. 2</u> - Percent Forward in Diffuser Wall Layers
Versus Distance along Diffuser Wall

AN INVESTIGATION OF PRESSURE FLUCTUATIONS AND STALLING CHARACTERISTICS ON ROTATING AXIAL-FLOW COMPRESSOR BLADES

Virginia Polytechnic Institute
and State University, Blacksburg, Virginia
Subcontract No. 8960-13

Professor W. F. O'Brien, Jr., Principal Investigator
Professor H. L. Moses, Principal Investigator
Mr. W. T. Cousins, Research Assistant
Mr. R. R. Jones, Research Assistant
Mr. W. F. Siedlecki, Research Assistant

Introduction

The overall goal of this research program is to provide a better understanding of stall-related phenomena in axial-flow compressors. The aspects of compressor performance that are of interest include the onset of stall, loss in performance, and the flow instabilities associated with stall.

The program involves both experimental and analytical efforts. A primary feature of the experimental work is the measurement of pressures directly on the rotor of test compressors, for flow conditions up to and including stall. For high-frequency-response measurements, special radio telemetry data transmission equipment has been developed for use with blade-mounted transducers. Experimental work is conducted employing a low-speed, single stage research compressor operating at approximately 2400 rpm, and a high-speed drive facility. A three-stage research compressor designed for operation in the 7500-17000 rpm range is used in the high-speed facility.

During the present reporting period, experiments were conducted with rotating stall in the low-speed research facility. Six on-rotor KULITE transducers were mounted on a rotor blade to study the pressure and lift fluctuations during the passage of a stall cell. Automatic data processing programs were devised to process pressure measurements and to calculate lift parameters, and an actuator-disc model of a compressor stage was constructed to apply the experimental results. In a separate investigation, a theoretical model was developed for the flow in a compressor cascade including boundary layer effects. The theory was evaluated in an experiment on the high-speed research compressor. An additional experiment studied the development of rotating stall in the first stage of this compressor.

Discussion

Present prediction methods for rotating stall and distorted inflow response in axial-flow compressors involve assumptions regarding the rotor blade flow time response to stalling disturbances. The usual procedure is to assume a time constant associated with a first-order model for the response, and to include this time constant in an unsteady compressor model. Present experiments in our low-speed facility are designed to

provide the first measurements of rotor blade flow response to stall-producing disturbances. High response, on-rotor pressure measurements are transmitted by radio telemetry from the rotor to a magnetic tape recorder and subsequently to a digital data processing system. The data system reconstructs pressure profiles on the rotor blade, and calculates lift, drag and moment information for the blade. This is done sequentially to determine the lift response of the blade from the measured pressure data.

Lift and drag information in the form of coefficients are used in an actuator disc model of the compressor stage. This non-linear model has been constructed in a manner similar to those of Takata and Nagano [1] and Adamczyk and Carta [2], but is designed to accept lift and drag information, rather than the conventional loss and turning angle information from cascade tests. Also, the lift response of the rotor blades is included as a correlation of the experimental data from the on-rotor experiments.

Initial experiments on the three-stage high speed research facility were conducted. This compressor has been designed to permit loading of the machine by operating a hydraulic actuator on the plenum discharge valve. Instrumentation includes pitot probes in the inlet of the compressor for flow measurement, a radially-traversing five-hole prism probe in the first stage stator row, and high-response total pressure probes located at two circumferential positions within the first stage stator. For the experiment, variable angle inlet guide vanes and stators were adjusted so as to produce initial stalling in the first stage rotor. Operating at 7500 rpm, the aerodynamic loading of the machine was increased in steps by closing the plenum valve. Tests were terminated when a rotating stall in the first stage rotor was encountered, as measured by the high response probes located at the 90% span position, 105° apart. Figure 1 shows the signals obtained from these probes, with the velocity defect and phase relation of the rotating stall cells clearly evident.

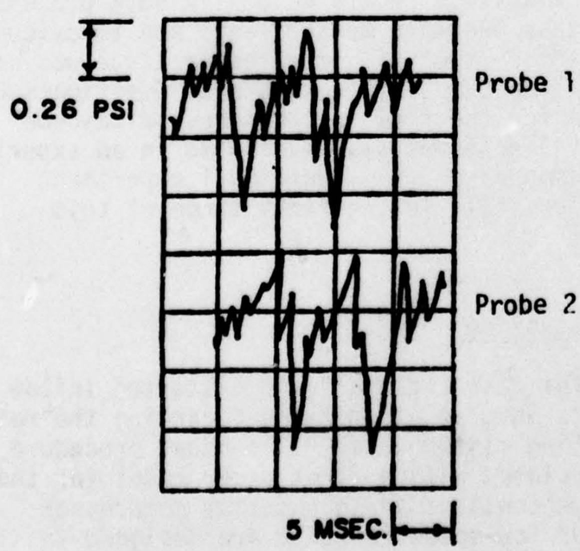


Figure 1 -
High Response Probe output with rotating stall, probes located in first stage stator row of high-speed research compressor.

The probe signals were cross-correlated employing an FFT analyzer, with the resulting cross spectrum shown in Figure 2. The frequency peak designated "A" corresponds to the occurance of the two rotating stall cells, with the additional peaks showing the harmonic content of the waveforms. It can be noted that the phase shift between the two signals (shown in the upper curve) is approximately 100°, corresponding to the angular separation of the high response probes.

With this successful initial experiment involving unsteady flow in the three-stage compressor rig, additional work is planned to determine the characteristics and stalling behavior of the machine at higher speeds. Stall prediction theories and distorted inflow response indices can be checked employing the machine, and results can be compared with those from the low-speed research compressor.

A second experiment employed the three-stage research compressor in steady flow to evaluate a new compressor flow prediction technique. Radial traverses were made with the five-hole prism probe behind the first stage rotor, measuring total pressure, dynamic head and yaw, and pitch angles. Total temperature measurements were made with a shielded iron-constantan thermocouple.

The referenced prediction technique involves an application of the simultaneous free stream-boundary layer calculation technique described in Ref. 3, and recently discussed in the Project SQUID Workshop on Separated Flows [4]. The method is developed for the calculation of steady, quasi-three-dimensional, subsonic compressible flow through a two-dimensional cascade of blades, including the effects of viscosity. The flow field is divided into two regions, a steady irrotational core flow modeled by the compressible stream function equation and blade surface boundary layers, modeled by the momentum and energy integral equations. The quasi-three-dimensional nature of the flow is introduced through streamtube contractions. The two regions are not solved in the typical iterative fashion however, but simulataneously, which allows solutions that include regions of separated flow. The exit flow angle is fixed by specifying equal velocities on the suction and pressure surface of the blade at the trailing edge plane. Total pressure loss coefficients for the fully mixed wake region are calculated from a control volume analysis of the exit region flow using calculated boundary layer parameters in the trailing edge plane. Thus the prediction technique allows the calculation of the typical blade element characteristics of deviation angle and total pressure loss coefficient for a wide range of incidence angles.

The spanwise performance of an axial-flow compressor stage is estimated by integrating the radial component of the momentum equation at the inlet guide vane exit/rotor entrance and rotor exit stations. Axial variations in radial velocity are neglected but entropy variations at both stations and energy addition along a streamline through the rotor are accounted for. A first approximation to the flow at both stations is obtained by assuming no losses. This provides information on the spanwise variation in rotor inlet conditions and streamline contraction. Blade element data is then calculated and used to

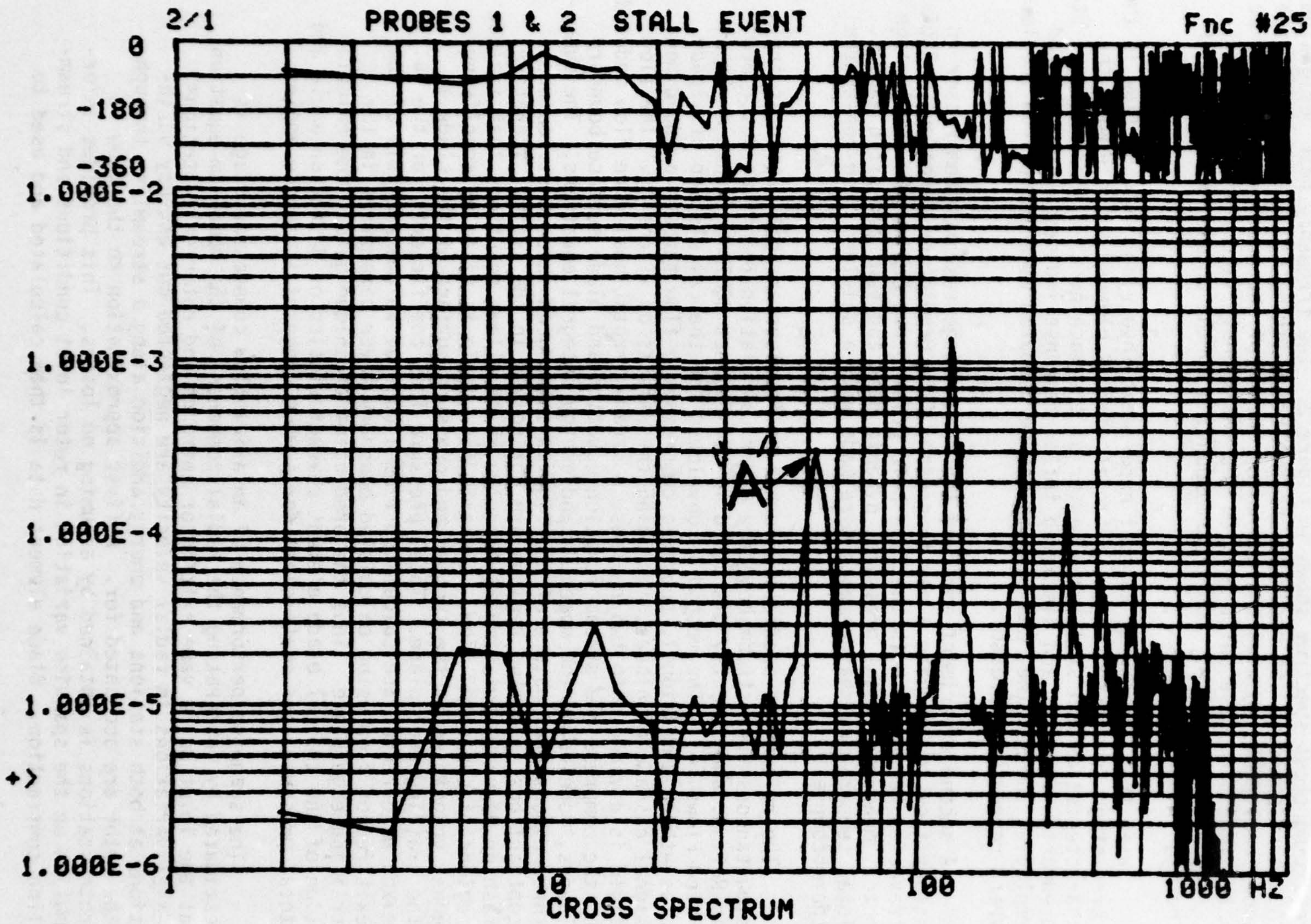


Figure 2 - Cross Spectrum of High-Response Probes Showing Rotating Stall at "A".

re-evaluate the stage performance. While such a procedure may require multiple iterations in a low hub/tip ratio compressor before a converged solution is obtained, only one cycle was employed in the present calculation.

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Semi-Annual Progress Report

EFFECTS OF TURBULENCE ON FLOW THROUGH AN AXIAL COMPRESSOR BLADE CASCADE

Colorado State University, Fort Collins, Colorado 80523
Subcontract No. 8960-15

Professor Willy Z. Sadeh, Principal Investigator

Introduction

The long-term objective of this research program is the determination of the effect of oncoming turbulence in reducing the aerodynamic losses in flow through a blade cascade of an axial-flow compressor at blade-chord Reynolds numbers ranging from $2x10^5$ to $5x10^4$. Within this Reynolds-number range the laminar separation of the boundary layer along the profile suction surface leads to prohibitively high aerodynamic losses and even to fully stalled blades. Significant diminution of the separation losses is achievable by arresting the growth of the laminar separation bubble and, furthermore, by preventing its very occurrence. These goals can be accomplished by fostering the development of a turbulent boundary layer on the profile suction side. Realization of such a boundary layer depends upon supplying oncoming turbulence of sufficient energy at scales commensurate with the thickness of prevailing profile boundary layer. Accumulation of turbulent energy at desired scales is produced through the selective amplification of outer turbulence. This organized turbulence amplification is governed by the stretching and accompanying streamwise biased tilting of cross-vortex tubes characteristic to forward stagnation flow. This research program is divided into three distinct phases addressed to methodically investigating the evolution of oncoming turbulence, its selective amplification at particular scales and the effect of the amplified turbulence on the boundary layer in flow: (1) about a circular cylinder-the first phase; (2) about several selected single airfoils-the second phase; and, (3) through a stationary blade cascade-the third phase. The first phase represents a diagnostic study conceived for supplying the basic guidelines for efficiently conducting the investigations of the other two subsequent phases.

Discussion

The research efforts are currently addressed to completing the objectives of the first phase and to initiating the second-phase research program. To start with, a paper describing some of the results of the visualization study of turbulence in flow about a circular cylinder (Project SQUID TR CSU-1-PU, October 1977) was accepted for presentation at and publication in the Proceedings of the Symposium on Aerodynamics of Transportation slated in Niagara Falls, New York from 18-20 June 1979. This symposium is organized by ASME, AIAA and SAE. The title of the paper is "Visualization of Turbulence in Flow About a Bluff Body."

Two technical reports dealing with two aspects of turbulence amplification in flow about a circular cylinder are presently being prepared. One technical report concentrates on the effect of amplified turbulence upon the separation on a circular cylinder at cylinder-diameter subcritical Reynolds numbers ranging from $5x10^4$ to $2x10^5$. The interaction of the amplified turbulence with the body boundary layer induced a relatively large downstream shift in the separation angle from 80 to about 125°. Simultaneously, the cylinder drag coefficient exhibited drastic reductions up to 40% of its laminar counterpart (no freestream turbulence). Both the separation angle and the drag coefficient obtained at this subcritical Reynolds-number range are of the same magnitude as those characteristic of much higher supercritical Reynolds numbers. The results indicate that adequate management of the amplification of the freestream turbulence by means of the stretching and tilting mechanisms leads to controlling the generation of a body turbulent boundary layer and, therefore, to governing of the separation angle and drag coefficient. A paper summarizing the results of this study tilted "Freestream Turbulence Effect on Laminar Separation on a Circular Cylinder" was accepted for presentation at the AIAA 12th Fluid and Plasma Dynamics Conference to be held in Williamsburg, Virginia from 23-25 July 1979.

The second technical report focuses on the evolution of freestream turbulence along the stagnation streamline as it is approaching the cylinder stagnation zone. This technical report includes a detailed description of the data that were amassed at six subcritical Reynolds numbers ($5x10^4$ to $2x10^5$). Data were collected at 21 stations and three different upwind positions of the turbulence-generating grid at each Reynolds number. All the results point out the occurrence of turbulence amplification at scales larger than the neutral one. Amplification ratios up to about 10 times were obtained with increasing scale. The results indicate, moreover, that one can govern the amplification depending upon the combination of the Reynolds number and the grid position.

A preliminary survey was conducted of the freestream turbulence evolution along the stagnation streamline of a symmetric NACA 65-010 airfoil with a chord (c) and span of 122 cm (48 in) and 183 cm (6 ft), respectively. These measurements were carried out at a zero angle of attack with the grid installed at an upwind distance of a half chord (x_{2g} = 0.5c, i.e., x_{2g} = 61 cm (24 in)). Amplification of the streamwise

component of the turbulent velocity (u_{2rms}) beyond 30% was monitored. A sample of the results at a profile-chord Reynolds number of $2x10^5$ is displayed in Fig. 1. In this figure, the amplification of the streamwise (or normal) turbulent velocity is portrayed as the stagnation zone of the airfoil is neared. The amplification ratio was computed based on the normal turbulent velocity at the station $x_2 = 0.05c$ (6.1 cm (2.4 in)) where the turbulence intensity (based on local mean velocity) was about 8%. Most of the amplification occurred within an upwir fetch up to 0.02c (2.44 cm (0.96 in)). The amplification ratio within this upstream range is displayed in the inset incorporated in Fig. 1.

It is important to stress that in flow about an airfoil the stretching of cross-vortex tubes is primarily dominated by their tilting around the body. The flow divergence around a streamline body at zero angle of attack occurs over a smaller spatial scale and much more rapidly than about a bluff body. This is due to the difference in the curvature of the stagnation zone of the body. 'Pure' stretching is consequently less significant in flow about an airfoil than around a circular cylinder. However, pure stretching plays a more substantial role with the increasing angle of attack of the streamline body. Elucidation of the relative importance of 'pure' stretching and tilting-induced stretching depending upon the body and its angle of attack is a matter of prime concern regarding the turbulence amplification. An analysis of the significance of these two mechanisms has therefore been initiated.

A visualization of the flow about an airfoil employing a symmetric NACA 65-010 profile is currently being carried out. This visualization is performed at a profile-chord Reynolds number of $2x10^4$ using white smoke composed of titanium dioxide. Preliminary results obtained at zero angle of attack reveal a turbulent flow pattern and a coherent substructure near the leading edge similar to those observed in the flow about a circular cylinder. A representative still showing the side view of a stretched cross-vortex tube is provided in Fig. 2. In this figure, the profile outline is traced out. The entrainment of the smoke filaments by an emerging cross-vortex tube near the airfoil leading edge is perceived. Particularly revealing is the distinct shape of the cross-vortex tube. With the consummation of the visualization study, a technical report will be submitted and a short motion picture will be produced. Both the survey of the turbulence development and the visualization indicate the realization of turbulence amplification and of a coherent substructure in flow around an airfoil under adequate approaching turbulence conditions.

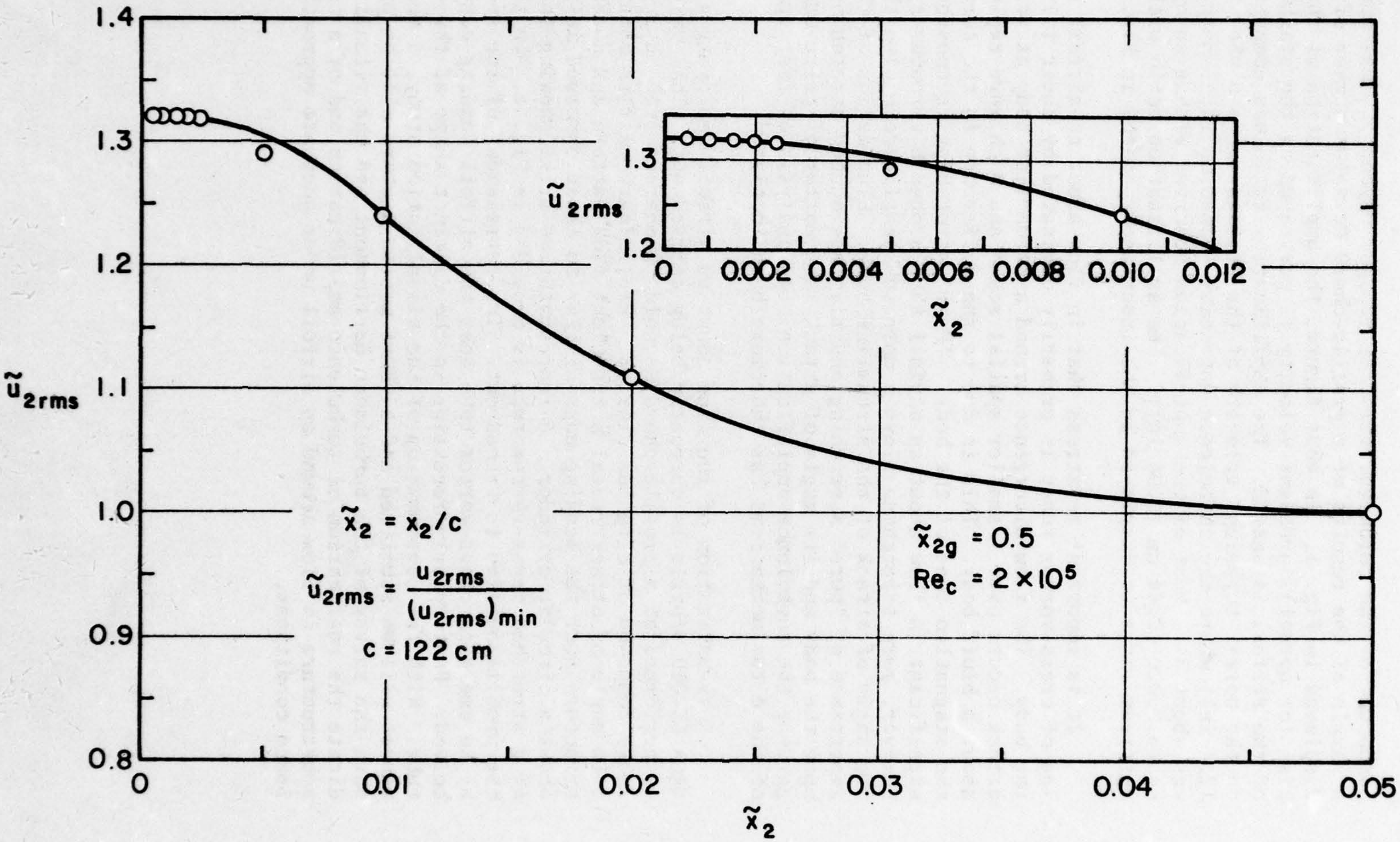

Fig. 1. Amplification of the streamwise turbulent velocity (rms) along the stagnation streamline in flow about a symmetric airfoil.

U_2 →

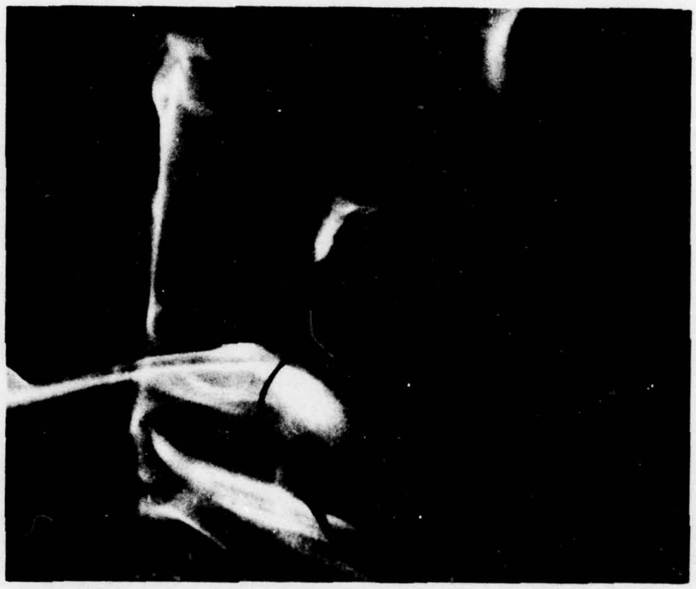

Fig. 2. Side view of a stretched cross-vortex tube near the leading edge of a symmetric NACA 65-010 profile at zero angle of attack and at a profile-chord Reynolds number of 2×10^4; f/5.6, 1/30 s; U_2 is the oncoming total velocity.

FUNDAMENTAL RESEARCH ON ADVERSE PRESSURE GRADIENT INDUCED TURBULENT BOUNDARY LAYER SEPARATION

Southern Methodist University, Dallas, Texas
Subcontract No. 8960-25

Professor Roger L. Simpson, Principal Investigator
Mr. G. P. Kokolis, Research Assistant
Mr. J. Yen, Research Assistant

Introduction

The problem of turbulent boundary layer separation due to an adverse pressure gradient is an important factor in the design of many devices such as jet engines, rocket nozzles, airfoils and helicopter blades, and the design of fluidic logic systems. Until the last five years little quantitative experimental information was available on the flow structure downstream of separation because of the lack of proper instrumentation.

In 1974 after several years of development, a one velocity component directionally-sensitive laser anemometer system was used to reveal some new features of a separating turbulent boundary layer [1]. The directional sensitivity of the laser anemometer system was necessary since the magnitude and direction of the flow must be known when the flow moves in different directions at different instants in time. In addition to much turbulence structure information, it was determined (1) that the law-of-the-wall velocity profile is apparently valid up to the beginning of intermittent separation; (2) that the location of the beginning of intermittent separation or the upstreammost location where separation occurs intermittently is located close to where the free-stream pressure gradient begins to rapidly decrease; (3) that the normal stress terms of the momentum and turbulence kinetic energy equations are important near separation; and (4) that the separated flowfield shows some similarity of the streamwise velocity U, of the velocity fluctuation u', and of the fraction of time that the flow moves downstream [2].

Based upon these results, modifications [3,4] to the Bradshaw, et al. boundary layer prediction method were made with significant improvements. However, this prediction effort pointed to the need to understand the relationship between the pressure gradient relaxation and the intermittent separation region structure. Another limiting factor for further refinement of the prediction of separated flows is the lack of fundamental velocity and turbulence structure information, especially in the backflow region. Thus, the objective of the current research program is to provide this information by using a directionally-sensitive laser anemo-

meter system to determine quantitatively the turbulence structure of a separating and separated turbulent boundary layer.

Discussion

This current research program was begun October 1, 1976, to obtain laser anemometer measurements of the separating flow of another adverse pressure gradient turbulent boundary layer for an airfoil or cascade blade type pressure distribution. Considerable effort has been made to avoid mean flow three-dimensionality and measurements indicate that it is minimal. Many measurements of U, V, $\overline{u^2}$, $\overline{v^2}$, $(U-V)/\sqrt{2}$, $-\overline{uv}$, the flow reversal intermittency, the skewness, and flatness of the velocity probability distributions, and velocity spectra are being obtained with the laser anemometer system in the vicinity of separation [5].

Figure 1 shows our most recent LDV measurements in the vicinity of separation. Intermittent flow reversal occurs downstream of the 127 inches location. As shown in the last Semi-Annual Progress Report (April - Sept., 1978), a logarithmic velocity profile region is distinct further on downstream until the detachment (fully-developed separation) location at 135.5 inches. Further downstream, the mean backflow velocity profiles have similar shapes and appear to scale on boundary layer thickness δ. The backflow region is strongly dominated by turbulent fluctuations that are greater than or at least comparable to the mean velocities, as shown in the last Progress Report. Since the freestream flow is observed to be rather steady, this means that the near wall fluctuations are not mainly due to a flapping of the entire shear layer, but due to turbulence within the separated shear layer. The mean backflow in this flow and the earlier flow [2] appears to be just large enough to satisfy continuity requirements after the shear flow separates to minimize streamwise pressure gradients. The backflow is never present all of the time.

It appears that since the mean backflow is governed by the turbulence and by continuity requirements, that it is unrealistic to try to force the mean shearing stress $-\overline{uv}$ to be a function of the local mean velocity gradient. Eddy viscosity and mixing length models infer that the fluctuations in velocity are small compared to the mean flow and that mean velocity gradients are not much different from instantaneous velocity gradients. Unfortunately separated turbulent flows like the type studied here do not satisfy these assumptions.

It does not appear that the "law-of-the-wall" type of velocity profile ($U^+ = f(y^+)$) based on a wall shearing stress can be valid for the backflow, unless significant turbulence energy production occurs near the wall. Turbulence energy balances deduced from the current series of experiments indicate that an almost negligible amount of turbulence energy production occurs in the mean backflow region as compared to normal and shear stresses production in the outer region. Figure 2 shows the terms of the energy balance that

are now available for a location just downstream of fully-developed separation. Large-scaled turbulence diffusion appears to be the main mechanism of bringing turbulence energy into the wall region. Since the mean advection of turbulence energy appears to be small in the backflow region, dissipation must balance this influx by diffusion. Classical turbulence energy arguments [6] indicate that production must equal dissipation in a logarithmic region governed by the law of the wall, which is not satisfied by the mean backflow region.

Figure 3 shows a good correlation of the mean velocity profiles in the backflow region of the current flow when normalized on the maximum negative mean velocity U_N and its distance from the wall N. A slightly poorer correlation results when δ is used instead of N. The law of the wall is not consistent with this correlation since both U_N and N increase with streamwise distance while the law-of-the-wall length scale ν/U_τ varies inversely with its velocity scale U_τ. Thus, it appears that representation of the backflow with the law of the wall does not have much basis.

During the coming report period further analysis of these data will be made and measurements of the W component will be attempted. A confocal backscattering reference beam arrangement is currently being tried.

On January 18-19, 1979, the Project SQUID Colloquium on Turbulent Flow Separation was held at SMU. Prior to the meeting, fifteen position papers on topics for fruitful future research were prepared by and circulated to the participants, who are active researchers on this subject. Attention was focused on five topics: semantics and terminology, measurements and techniques, flow modelling, unsteady effects, and control of separated flow. A summary report will be prepared during the next report period.

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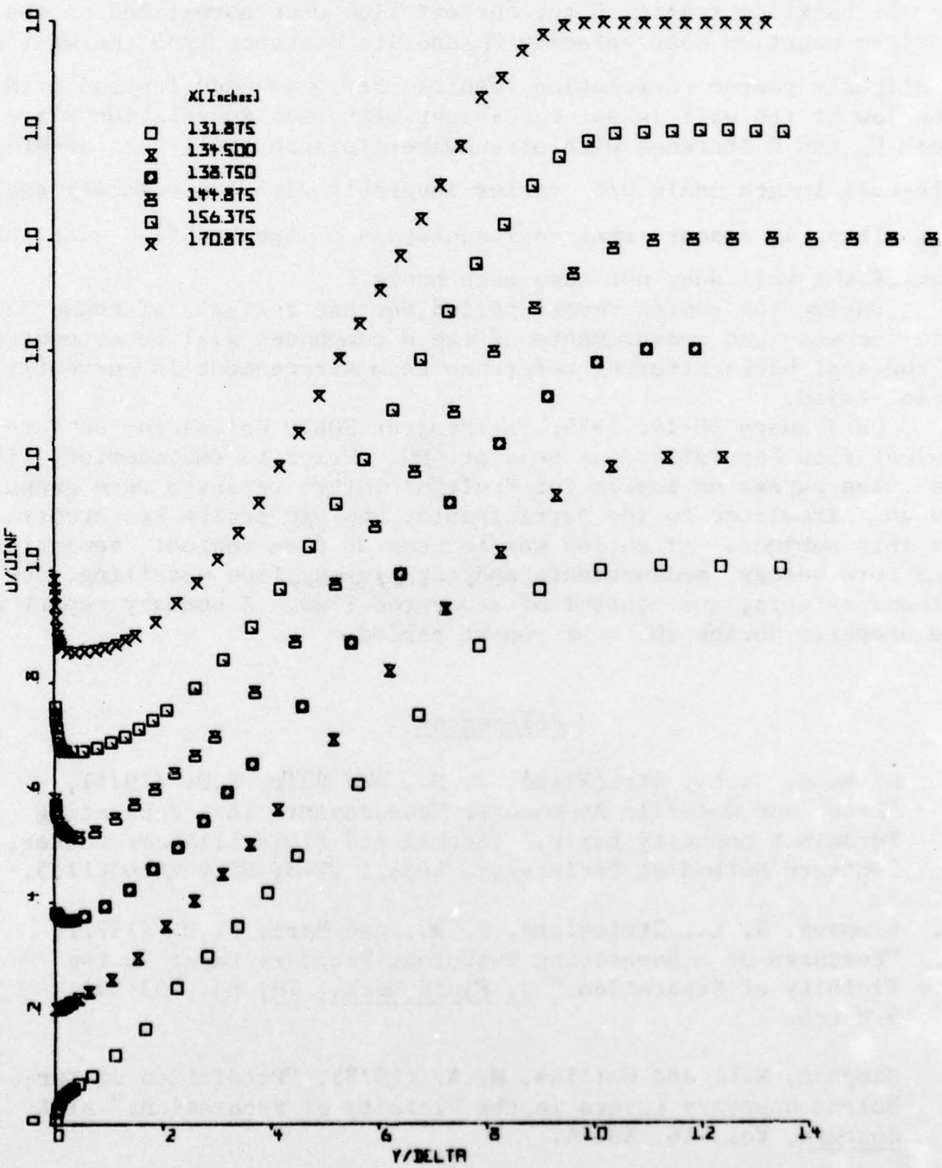

Figure 1. Mean velocity profiles at several locations, U/U_∞ vs. y/δ.

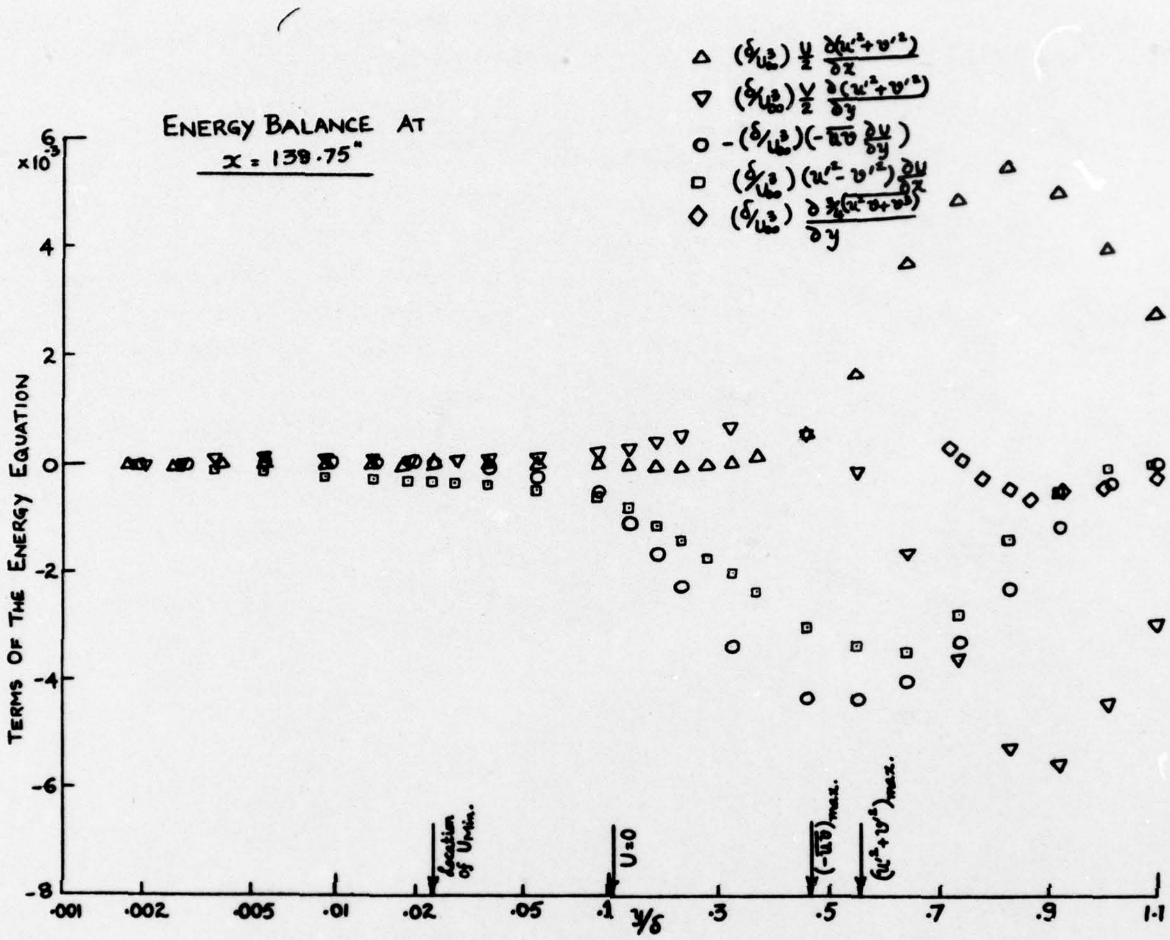

Figure 2. Mean turbulence energy equation terms a short distance downstream of fully-developed separation or detachment.

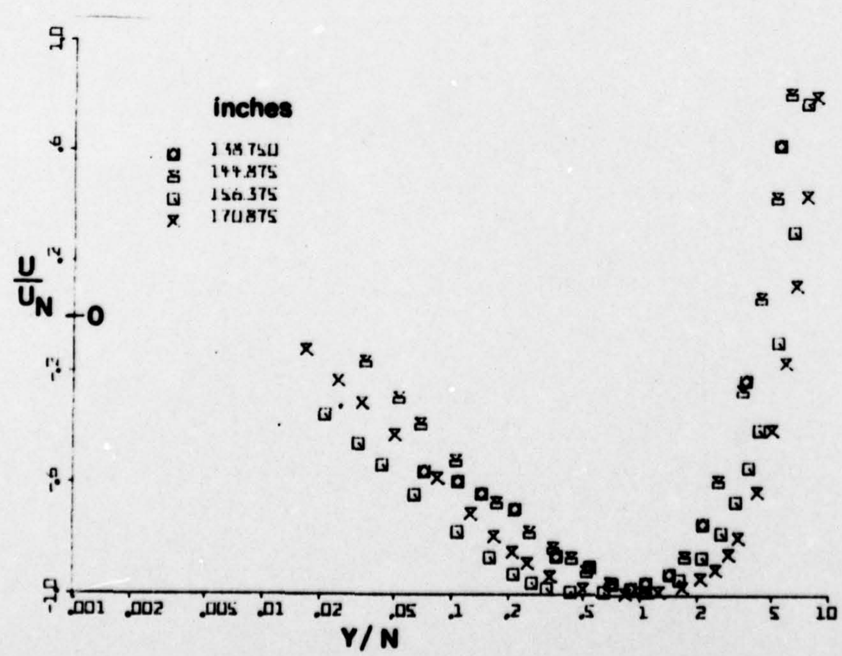

Figure 3. Backflow mean velocity profiles.

II. COMBUSTION AND CHEMICAL KINETICS

TL-940

March 1979

PREPARATION OF MANUSCRIPT ON IONIZATION IN FLAMES

AeroChem Research Laboratories, Inc., Princeton, NJ 08540
Subcontract No. 8960-32

Hartwell F. Calcote, Principal Investigator

Introduction

The purpose of this program, initiated 1 September 1978, is to critically organize the extensive literature on ionization in flames. This literature includes not only fundamental studies of the mechanism of ionization in flames, but the use of flames to determine ionization potentials of certain oxides, the use of flame ionization to measure neutral species concentrations, and the use of flames to measure reaction rates involving ions.

Discussion

Much of the pertinent literature has been collected and cataloged into chapters. Two chapters, one on "The Effect of Electric Fields on Flames" and the other on "Soot Formation" are close to completion. These things always progress at a slower pace than anticipated because so much of the available data just cries out to be reinterpreted and this leads one into the trap of re-evaluating the data rather than organizing it.

A SHOCK TUBE STUDY OF H_2 AND CH_4 OXIDATION WITH N_2O AS OXIDANT

University of Missouri, Columbia, Missouri
Subcontract No. 8960-21

Prof. Anthony M. Dean, Principal Investigator

Introduction

The study of oxidation reactions in shock tubes has been stimulated by the use of fast, accurate numerical integration routines. Now it is possible for kineticists to more definitively test various oxidation mechanisms by a detailed comparison of calculated and observed concentration-time profiles. Although the $H_2/O_2/Ar$ and $H_2/O_2/CO/Ar$ systems have been successfully studied by this approach, extension to even simple hydrocarbon systems like CH_4/O_2 has been limited by lack of reliable high temperature rate constants. A common practice has been to extrapolate low temperature flow system data to the temperature range of interest. Unfortunately this approach can lead to serious errors; recent studies have convincingly demonstrated that many reactions of importance in combustion mechanisms exhibit markedly "non-Arrhenius" rate constants. In this light it appears to be most desirable to measure rate constants in the same high temperature regime where they will be used to test the combustion mechanisms. However, it is equally important that these data be obtained from relatively simple systems where assignment of the desired rate constant is not contingent upon proper assignment of a complex mechanism and the associated rate constants.

The basis of our SQUID work is the substitution of N_2O for O_2 in combustion studies. Earlier work in our laboratory [1] suggested that the high temperature dissociation of N_2O might serve as a useful source of oxygen atoms. Use of N_2O as the oxidizer in combustion studies would then allow one to study the rate of the reaction between oxygen atoms and the fuel. The main advantage of the substitution is that the kinetics are simpler; here one need not consider reactions of oxygen molecules as in a normal combustion system. Our initial efforts in the SQUID program concentrated on further refinement of the N_2O dissociation kinetics and measurement of the recombination rate of oxygen atoms and carbon monoxide [2]. The substitution technique was then tested on a series of experiments with hydrogen as the fuel [3]. Here it was possible to compare the rate constant for the reaction $O + H_2 \longrightarrow OH + H$ obtained via our $N_2O/H_2/CO/Ar$ work with that obtained from the traditional studies of $H_2/O_2/Ar$ system. Good agreement was obtained; it was also possible in this work to obtain high temperature rate constants for $OH + CO \longrightarrow CO_2 + H$ and $H + N_2O \longrightarrow N_2 + OH$.

With the validity of the technique established, our attention then focused upon study of the methane system. Here there is appreciable uncertainty in rate constant assignments for important reactions. Analysis of our data at high temperature (2400<T<3000 K) yielded values for the rate constant of the reaction $O + CH_4 \rightarrow CH_3 + OH$ much higher than one would obtain from the usual extrapolations of the low temperature data. This value was in good agreement with a very recent high temperature measurement. These results reinforced the thesis that rate constants used in modeling calculations should come from high temperature measurements. Analysis of the methane data at lower temperatures (1800<T<2200 K) suggested unsuspected complexities in the mechanism. Subsequent experiments strongly suggested that reactions of formaldehyde (CH_2O) were responsible. As a result of this observation, our attention shifted to a detailed study of these reactions. Our initial efforts were aimed at the pyrolysis of CH_2O [4]. Here it was seen that CH_2O decay was influenced primarily by the CH_2O dissociation reaction and by hydrogen atom attack upon CH_2O. It was not possible to completely separate the effects of these reactions, and thus unambiguous rate constant assignments were not possible. However, it was evident that the dissociation rate constant was much lower than that previously reported.

Discussion

In the last six months we have completed a study of CH_2O oxidation [5]. This research has had two functions: (1) To attempt to complement the pyrolysis study by separating the contributions from the reactions

$$CH_2O + M \rightarrow HCO + H + M \qquad (I)$$

$$CH_2O + H \rightarrow HCO + H_2 \qquad (II)$$

so that rate constant assignments could be made. (2) To obtain more direct information about the reactions

$$CH_2O + O \rightarrow HCO + OH \qquad (III)$$

$$CH_2O + OH \rightarrow HCO + H_2O \qquad (IV)$$

Here it was possible to assign rate constants for these four reactions from analysis of $CH_2O/CO/O_2/Ar$ systems. These assignments were checked in a series of studies where N_2O replaced O_2. Perhaps the most significant conclusion of this work is that the rate constants for Reactions (I) and (IV) appear to be much lower than those currently utilized in modeling calculations.

With these rate constants in hand, it was now possible for us to attempt to reanalyze our earlier data on methane. Use of the new rate constants have considerably improved the situation here; it is now possible to get good agreement for most of the observables in those experiments. The analysis is not yet complete, but it would appear that it will be possible to obtain reliable high temperature estimates of rate constants for the following reactions:

$$O + CH_4 \rightarrow CH_3 + OH \qquad (V)$$

$$OH + CH_4 \rightarrow CH_3 + H_2O \qquad (VI)$$

$$O + CH_3 \rightarrow CH_2O + H \qquad (VII)$$

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HIGH-TEMPERATURE FAST-FLOW REACTOR CHEMICAL KINETICS STUDIES

AeroChem Research Laboratories, Inc., Princeton, NJ 08540
Subcontract 8960-16

Arthur Fontijn, Principal Investigator

Introduction

Reliable quantitative knowledge of the kinetics of free metal atom and metal oxide species is required for a better understanding and description of (i) the burning of metallized propellants and (ii) the exhaust properties of rockets using such propellants. Suitable techniques for obtaining such kinetic information were unavailable until we adapted the tubular fast-flow reactor technique to reach temperatures up to 2000 K (1). This development has extended an essentially room temperature technique to being capable of being used for making measurements in the temperature range of conventional high-temperature techniques such as flames and shock tubes.

The agreement between (extrapolated) rate coefficients obtained from high and low temperature determinations by separate techniques is often poor. It is also becoming apparent that, for many reactions, Arrhenius-type plots of rate coefficients vs. T covering ranges on the order of 1000 K or more show distinct upward curvature with increasing T (e.g. Refs. 2-4), thus making extrapolation of k(T) data over wide temperature ranges a procedure of doubtful validity. For reliable k(T) measurements it is desirable to use a single technique to span the entire T-range of interest. For the 300-2000 K range our high-temperature fast-flow reactor (HTFFR) technique provides such a technique for metallic species.

Discussion

In the reporting period work under this contract was completed. The final study concerned the reaction

$$Al + SO_2 \rightarrow AlO + SO \qquad [1]$$

on which additional data were obtained and a manuscript (5) was prepared.

The $k_1(T)$ measurements spanned the 700-1600 K range for which the rate coefficient expression $k_1(T) = (1.6 \pm 0.8) \times 10^{-10} \exp[-(2000 \pm 300)/T]$ ml molecule^{-1} s^{-1} was obtained. This rate coefficient is significantly larger than that for the Al + CO_2 reaction over the same temperature range (4), which can be attributed to the fact that only the SO_2 reaction can proceed by an electron jump mechanism for the vibrational ground state of the oxidant. This $k_1(T)$ indicates with 95% probability that the Al–O bond dissociation energy is $\geq$ 126 kcal mol^{-1}, somewhat larger than the 120 $\pm$ 2 kcal mol^{-1} range given in the JANAF tables.

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ISOTOPIC STUDIES OF THE CHEMICAL MECHANISMS OF SOOT NUCLEATION

Kansas State University, Manhattan, Kansas
Subcontract No. 8960-33

Professor T. W. Lester, Principal Investigator
Professor J. F. Merklin, Co-Principal Investigator
Mr. S. N. Vaughn, Research Assistant

Introduction

The purpose of this research is to determine experimentally the principal chemical mechanisms of soot nucleation from possible constituents of alternate gas turbine fuels. A primary motivation for this research is a desire for a better understanding of the early stages in the formation of high molecular weight hydrocarbons from simpler ones. While global routes to soot formation have been identified and many hydrocarbons in the process catalogued, there is still a great deal of uncertainty about the important reactions(1). In this study the chemical mechanisms of soot nucleation from aromatic and heteroatomic constituents of synthetic fuels will be studied with the use of model compounds and a single pulse shock tube. Specifically of interest will be whether soot nucleation occurs via polymerization of the aromatic molecules or by condensation of smaller molecules which resulted from fragmentation of the parent hydrocarbon.

Discussion

Since the early Nineteenth Century, attempts have been made to provide a sufficiently complete model of soot formation. A number of experimental apparatus have been employed in this quest including premixed and diffusion flames, well-stirred reactors, and shock tubes. Of the above, the shock tube has distinct advantages in studying the nucleation of soot and the complex reactions preceeding it at temperatures and pressures comparable to those attained in modern combustors. This utility has been highlighted in recent studies of soot oxidation

by Park and Appleton(2) and soot coagulation by Graham, et al.(3) To unravel the complicated chemistry involved in the nucleation process, this study is utilizing a number of chemical and optical diagnostic techniques in conjunction with the single pulse shock tube.

The period through 30 June, 1979 will be devoted primarily to the optimization of the sampling techniques in the study of benzene pyrolysis. Insofar as Graham, et al. have postulated that the soot yields they observed were due to ring polymerization at temperatures below 1750 K and ring fragmentation followed by condensation of radical fragments above that temperature, gas chromatography and mass spectrometry of stable products of benzene pyrolysis will be used to verify that this is in fact the case. It should be noted that the discrimination of these two routes is dependent on quenching the reaction sequence as quickly as possible. Towards this end, the rarefaction will be brought into the reflected shock region within 100μsec of the initiation of the pyrolysis reactions by passage of the reflected shock. To minimize the uncertainties of reaction time, the reactants are confined initially to a ball-valve which is rotated in line with the tube just prior to the diaphragm rupture. In this way the reactant is compressed behind the reflected shock to roughly 5 mm axially which results in a variation in reaction dwell time of less than 10μsec.

After the reaction is quenched, the ball valve will be closed and samples will be withdrawn from the reaction zone for analysis. Product analysis by gas chromatography with flame ionization detectors will be able to discriminate between the routes proposed by Graham et al. for the pyrolysis of benzene(3). The products from ring polymerization will be biphenyl, terphenyl, quaterphenyl and higher molecular weight polyphenyls. These products are easily separated in a gas chromatograph due to their differences in boiling point. It may be also possible to monitor benzene disappearance in the analysis of condensed products. The products from the ring fragmentation route will be significantly different in character. Ring fragmentation will form acetylenic type radicals or stable species. These products could react among themselves and form polyacetylenes or add to a benzene molecule and form substituted benzene compounds or rearrange to form condensed polyaromatics like naphthacene or anthracene. The two routes for benzene pyrolysis and their behavior with temperature can be defined since the pyrolysis products will be significantly different.

The use of the gas chromatograph and the mass spectrometer compliment one another in the analysis of products. The mass spectrometer will provide information on the structure of the products, whereas the gas chromatograph will measure quantitatively the yields of these products.

To compliment the product analysis, emission and absorption spectroscopy are to be used to provide the time-resolved qualitative behavior of intermediates during the process of ring polymerization or rupture. For instance, we anticipate that rupture of the ring structure will lead to considerably different CH and C_2H_2 emission profiles.

As the molecules or molecular fragments coalesce to larger gas phase molecules, the onset of absorption of light by molecular electrons will shift to longer wavelengths. The onset of optical absorption by benzene in the gas phase is about 270nm. The onset of optical absorption by products from benzene condensation (e.g., biphenyl, terphenyl) absorb at longer wavelengths than does benzene. As the molecules become larger, the onset of absorption is at longer wavelengths. If ring rupture occurs, leading to acetylenic fragments which condense to form polyacethylenes, this shift in optical absorption will also occur. This type of measurement was recently done by Cundall et al. in the pyrolysis of acetylene(4). They measured the growth of the optical absorption at various wavelengths in the near ultraviolet as a function of temperature and time, and related this growth to the formation of gas phase polyacetylenes before the appearance of soot particles.

Light from a xenon or mercury lamp is condensed into a parallel beam and passed through the observation ports of the shock tube. The transmitted light is focused on the entrance slit of a Jarrell-Ash 1/4 meter monochromator, set at a predetermined wavelength. The transmitted intensity at this wavelength before, during, and after the shock will be monitored by a photomultiplier. The wavelength will be varied from 270 nm to 400 nm. The increase in absorption at various wavelengths will be a qualitative measure of the extent of the condensation of benzene or molecular fragments into larger molecules.

Finally, either laser extinction at two wavelengths or laser extinction and scattering will be used to give estimates of the soot yield in runs where the reaction time is maintained sufficiently long that coagulation of the soot particles has started. Both techniques can give reasonable estimates of the soot yield once the particles have reached 100 Å in diameter. Because both are critically dependent upon a relatively better knowledge of the complex refractive index than is now available, size measurements will not be inferred from the data; furthermore, both techniques give only the first moment of the distribution and little is known, other than by electron microscopy work such as performed by Wersborg, et al.(5), of the higher moments of soot polydispersions. Nevertheless, the measurements of soot yield can serve as a powerful complimentary diagnostic tool to distinguish ring rupture versus condensation. This appears to be the case based on the work of Graham, et al. and also Davies and Scully(6) wherein the lower soot yields from compounds with heteroatoms compared to aromatics was attributed to the ring rupture. Thus, the evidence indicates that soot yields under controlled conditions serve as a window to the earliest stages of nucleation.

Hence during the period through 30 June 1979, a number of complimentary diagnostic tools will be used on the pyrolysis of benzene to test the hypothesis of rupture or polymerization as the primary initiation step. Once these tests are complete, the evaluation will be extended to heteroaromatic compounds such as thiophine and pyridine. By 31 August 1979, it is anticipated that the question of whether the soot nucleation is initiated by bond rupture or polymerization will be answered and a tentative resolution of over what temperature ranges in pyrolysis each mechanism is dominant.

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PYROLYSIS OF SYNTHETIC FUELS USING THE LASER-POWERED HOMOGENEOUS PYROLYSIS TECHNIQUE

Cornell University, Ithaca, New York
Subcontract No. 8960-35

Professor W. J. McLean, Principal Investigator
Ms. W. Lei, Research Assistant

Introduction

While a complete and detailed understanding of carbon particle formation and destruction in gas turbine combustors is not yet available, it is generally accepted that important luminosity and soot formation effects are intimately related to the rapid pyrolysis which occurs when the fuel is injected into the combustor. It is during this pyrolysis phase of the combustion that soot precursors, such as polyacetylenes and polyaromatic compounds, are formed. The objective of the present program is to experimentally investigate the pyrolysis of compounds characteristic of high carbon-to-hydrogen ratio synthetic fuels, with particular emphasis on the formation of soot precursors during these pyrolysis processes.

The pyrolysis studies are being carried out using the laser-powered homogeneous pyrolysis (LPHP) technique. This technique provides a method for homogeneously heating a gas sample by using small amounts of SF_6 or SiF_4, which have large absorption cross sections for a specific rotational line of a CO_2 laser. The fast vibration-translation relaxation time for the absorber then serves to rapidly heat the surrounding gas while the test cell walls remain near their initial temperature. Typically, the small quantities of the hydrocarbon reactant material in an argon diluent are heated rapidly to temperatures in the range 500 to 1800 K using irradiation times from fractions of a second up to several minutes. The pyrolysis products are rapidly cooled upon termination of the laser irradiation, and the progress of the decomposition reactions can be followed by analyzing the pyrolysis products by standard gas chromatographic and mass spectrometric techniques. Alternatively, time resolved pyrolysis reactions may be followed by continuous techniques such as resonance absorption or molecular beam mass spectrometry.

DISCUSSION

The current Project SQUID Program started in June 1978. Analytical studies have been essentially completed, and the first phase of the experimental program is in progress.

The objective of the analytical study was to determine temperature and velocity distributions inside an LPHP cell and to use these results to determine temperature-time histories for various parcels of mass within the cell. The analysis is complete and temperature-time maps are being prepared.

The experiments in progress are intended to measure the temperature distribution inside the LPHP cell by fine wire thermocouple. The effect of direct radiation heating and natural and forced convection cooling on the thermocouple reading is being evaluated by performing tests under vacuum, as well as with Ar and Ar-SF_6 mixtures in the cell. The data obtained under vacuum conditions enable calibration for the influence of the incident laser radiation on thermocouple reading. With argon in the cell the thermocouple can be calibrated for natural convection cooling effects. Initial results indicate that thermocouple temperature measurements are feasible in this system and that the measured temperatures are approximately equal to bulk gas temperatures obtained in the analytical studies. Further studies will emphasize pyrolysis of standard compounds and comparison of results with existing data.

Semi-Annual Progress Report

FUNDAMENTAL STUDIES ON TURBULENT, SWIRLING JET IGNITION

Princeton University, Princeton, New Jersey 08544

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Dr. A. Gany, Research Staff Member
Mr. S. F. Parker, Ph.D. Candidate

Introduction

This program involves a study of the relationships between the swirl and turbulence properties of a combustor and the ignition and flammability phenomena. The study centers on an experimental axisymmetric configuration with two concentric flows. The outer flow is always air while the inner flow is some combination of methane, air, and additional nitrogen (for temperature control). A theory will be developed to analyze the swirling, turbulent reactive flow. Comparisons with experiment should allow the development of a predictive capability.

Discussion

The experimental fabrication is almost complete and the assembly should be completed by the middle of April. The LDV instrumentation and data handling equipment are already operative.

Separate control of the inner and outer mass flows and swirl velocities is achieved in the experimental design. The outer air flow will be pumped through a settling chamber and then past radial vanes (for swirl control) before entering the test section. The inner flow can be simply air for cold flow studies; it can be methane and nitrogen for diffusion

flame studies; or it can be a combustible mixture of methane, air, and nitrogen for premixed flame studies. Velocity measurements (especially axial and azimuthal components) will be made via our LDV apparatus; both mean velocities will be determined.

All components in the radial inlet sections have been carefully designed to minimize large scale fluctuations due to vortex shedding. Preliminary measurements in a cold flow case should occur before the end of April. From these, the roughness of the flow could be determined before proceeding to the combustible cases.

The theoretical effort in the program involves the development of a mathematical model which can be solved via computation. The study which began before the subcontract was awarded involved a planar, mixing layer. That portion of the study is almost completed and should be reported in a Project SQUID Report. The axisymmetric case will be examined next.

The planar, mixing system, perhaps the most fundamental problem of turbulent, reacting shear flows, is analyzed via several model approaches and comparisons are made. Various forms of mixing-length theory, k-ε theory and k-ω theory, are employed with both Favre and time-averaging. The nonreacting limit with temperature and density gradients are fully examined. Comparisons are made amongst the computational results of the various nonreacting models and also with existing experimental results; both mixing layer thickness and profile shapes are examined. Ignition delays for both pre-mixed combustibles and for initially-unmixed reactants are determined with the various models. Comparisons between results of the reacting models are made. A coordinate transformation is employed to remove the singularity which results at the mixing layer edges where the turbulent viscosity and diffusivity go to zero. An iterative, quasi-linearized implicit finite-difference scheme was employed for the parabolic systems of equations. Similar solutions were obtained in the nonreacting limit. Results indicate that significant differences occur amongst the models in both the nonreacting and reacting cases. The differences are greater for temperature and density profiles than for velocity profiles. The comparison between theory and data is not good but that finding is not conclusive since the extant nonreacting experimental data with variable density are limited to lower Reynolds number while the theories are valid in the limit of very high Reynolds number. The theory for the reactive system indicates significant sensitivity to temperature and partial densities.

III. MEASUREMENTS

TURBULENT STRUCTURE DETERMINATION BY RAMANOGRAPHY

Yale University, New Haven, Connecticut
Subcontract No. 8960-29

Professors R. K. Chang and B. T. Chu, Principal Investigators
Mr. M. Long, Assistant in Research
Mr. B. Webber, Assistant in Research
Mr. D. Murphy, Assistant in Research

Introduction

The long-term objective of our research is to develop new spectroscopic techniques which are capable of providing fundamental information and testing existing models on turbulence and combustion. We are presently using the following techniques to determine the concentration spatial profile within the flow-field of a jet: (1) Mie scattering from aerosols seeded in a jet to determine the 2-D instantaneous (9 μsec) concentration profile; (2) spontaneous Raman scattering to obtain the 2-D time averaged CH_4 concentration profile; and (3) large angle BOX-CARS with two sheets of radiation to simultaneously measure the instantaneous CH_4 concentration from each point along a line (1-D).

Discussion

Mie Scattering

If we assume that the concentration profile of aerosols in a flow-field is representative of the gas concentration profile, an instantaneous "picture" of the Mie scattering from a plane intercepting the flow-field of a jet can provide information on the spatial distribution of the gas concentration. The argon ion laser light is focused in one dimension by a 25 cm focal length cylindrical lens giving a sheet of illumination 1 cm x 1 cm x 100 μm passing through the center of the jet.

The axisymmetric jet used in the experiment is a preliminary design with a diameter of 2 mm and is seeded with sugar aerosols (less than 1 μm in diameter) produced by an aerosol generator (Sierra Instruments Model 7330). The Mie scattered light is collected normal to the illuminated sheet by a lens and is focused on the face of the TV camera (PAR OMA 2 with SIT detector head) by another lens. The TV camera is electronically gated on for 9 μsec by a high-voltage pulser. The 2-D image is divided into a 100 x 100 element array and the digitized information is stored in a PDP 11/34 computer which controls the entire experiment.

From the instantaneous 2-D Mie intensity recordings, we were able to obtain the following properties of the jet at a Reynolds number of 4400: (1) Average 2-D concentration $\overline{C}(x,z)$ [x-axis along the jet downstream direction and z-axis in the illuminated sheet] obtained from 60 instantaneous concentration pictures. (2) Average 2-D non-dimensionalized concentration contours, $\overline{C}(x,z)/C_{max}(x)$, where $C_{max}(x)$ is the maximum concentration at distance x downstream. (3) 2-D rms concentration fluctuation with 60 instantaneous concentration pictures. (4) Spatial correlation in the concentration fluctuation in the z direction for a specific point along z and at fixed x values. Our results were published in Appl. Phys. Lett. 34, 22 (1979).

Spontaneous Raman Scattering

Ramanography has the disadvantage that spontaneous Raman scattering from gases is much weaker than Mie scattering from seeded aerosols in the flow-field. The major noise source in Ramanography is photon shot noise, while that for Mie scattering is from marker shot noise caused by the small number of aerosol particles per unit volume.

The Raman scattered light from a 2-D illuminated sheet formed by the laser focal volume (1 cm x 1 cm x 100 μm thick) was too weak to detect. In order to increase the scattered light intensity, a quasi 2-D sheet formed by having the laser track undergo multiple reflection from two concave cylindrical mirrors was used. The resultant Raman scattering intensity from the CH_4 jet was detected by a cooled SIT TV camera. This quasi 2-D intensity profile was normalized by the spatial inhomogeneity of the "striped" illumination sheet, collection optics throughput, and camera response.

The time averaged CH_4 concentration profile was determined at a Reynolds number of 4950. By changing the interference filters from those selecting the CH_4 Raman signal to those which select the N_2 Raman signal, the concentration of N_2 (present in the surrounding air) was also determined. The N_2 concentration profile was essentially the inverse of that of CH_4 with CH_4 gas emerging from the nozzle. The N_2 concentration profile was also measured with SF_6 gas emerging from the nozzle. Comparison of our Raman results on the CH_4 and N_2 concentration profiles was made with the time averaged Mie scattering data. The Raman and Mie results

are in qualitative agreement. The main differences between the seeded and unseeded jets are attributed to changes in the fluid viscosity and density caused by seeding and to the sensitivity of our jet to initial conditions. Based on our Raman results with a cw laser, we are now able to estimate the energy needed from a pulsed laser in order for us to obtain the instantaneous concentration profile by the spontaneous Raman technique.

BOX-CARS

In collaboration with Dr. Alan C. Eckbreth of United Technologies Research Center, we have demonstrated that spatially resolved coherent anti-Stokes Raman generation along a line can be obtained by using sheets of laser radiation and large angle phase matching geometry. The two ω_1 beams are focused with cylindrical lenses to form overlapping, coplanar sheets. The ω_2 ($\omega_2 = \omega_1 - \omega_{CH_4}$) beam is focused by a spherical lens and directed to lie in the plane of the ω_1 sheets and to cut across their intersection region, thus defining a line over which all three input beams overlap. The ω_3 ($\omega_3 = 2\omega_1 - \omega_2$) beam then radiates in the phase matched direction perpendicular to this line. With such large crossing angles among the two ω_1 and ω_2 beams, the overlap region is unambiguously resolved, so there is no anti-Stokes generation other than at the line of intersection. An optical multichannel analyzer detects the signal intensity at ω_3 as a function of position along the line and thereby enables us to instantaneously determine the CH_4 density as a function of position.

We are presently using the optical multichannel analyzer in only its 1-D scanning mode. By using a broad bandwidth dye laser beam, a spectrograph to wavelength disperse the anti-Stokes signal in the direction orthogonal to the probed line, and the 2-D capability of the camera, it should be possible to deduce the spatially resolved vibrational and rotational temperature, as well as the concentration profile, along a line in a flame after a single laser pulse. This will then enable us to calculate the spatial correlation functions of temperature and concentration fluctuations which are of interest in turbulence modeling.

Semi-Annual Progress Report

CARS INVESTIGATIONS IN SOOTING AND TURBULENT FLAMES

United Technologies Research Center
East Hartford, Connecticut 06108
Subcontract 8960-28

Alan C. Eckbreth, Principal Investigator

Introduction

Laser Raman spectroscopic techniques for combustion diagnostics have undergone considerable development in the past several years and are now being employed in a variety of fundamental flame investigations. Instrumentally however, practical combustion devices possess flame environments which differ markedly from those typically (laminar premixed, hydrogen diffusion) employed in fundamental studies. Practical devices contain flames which can be highly particulate laden and hence, luminous, if hot, and turbulent. These conditions lead to a variety of severe, naturally occurring or laser induced interferences which must be overcome. Of these, laser modulated particulate incandescence appears to be the most severe. When the soot particulate loadings become moderate, on the order of 10^{-8}gm/cm^3 or larger, the spontaneous Raman signal to laser modulated soot incandescence interference ratio can become unacceptably low for measurement purposes.

Coherent anti-Stokes Raman spectroscopy (CARS) appears as an attractive alternative to spontaneous Raman scattering for practical combustor diagnosis. First, the CARS process generates signals generally several orders of magnitude greater than those possible with spontaneous Raman scattering. Second, the CARS radiation emerges as a coherent beam which can be completely collected using high f number collecting optics and spatial filtering. This not only leads to high signal collection efficiency, but low interference collection as well due to the greatly reduced solid angles employed. CARS signal strengths appear adequately large to overcome interferences from both natural background luminosity and laser modulated particulate incandescence. However, CARS generation in sooting flames had not been demonstrated. In sooting flames, there is the potential for the generation of nonlinear interferences from soot particulates and soot vaporization products. The objective of this research was to address CARS generation in sooting flames, to examine and develop techniques to suppress nonlinear interferences, and to perform CARS temperature measurements in such flames. Such a program logically precedes measurement attempts in actual research scale combustors.

Investigations of CARS in highly sooting, laminar and turbulent propane diffusion flames have been completed and a technical report detailing this research will appear shortly (Ref. 1). For a CARS pump wavelength of 5320 Å from a frequency-doubled neodymium laser, interferences can occur at very high soot densities. For CARS from N_2, there are both incoherent and coherent components to the interference. Numerous experiments were conducted in an attempt to understand the origin of these interferences. The incoherent interference arises primarily from anti-Stokes fluorescence from C_2 excited by Stokes laser absorption. The C_2 is created by the laser vaporization of soot particulates (Ref.2,3), which has now been shown to occur even on a nanosecond time scale. C_2 Swan band ($A^3\ \pi_g$ - $X'\ ^3\pi_u$) absorptions of the Stokes laser terminate on vibrational levels in the excited electronic state , which are the initial levels for emissions in the N_2 CARS spectral region. The coherent interference arises most probably from electronically-resonantly enhanced wave mixing in the C_2. The Swan transition (1,0) resides at 4737 Å midway between the N_2 CARS ground state band at 4733 Å and the hot band at 4740 Å. Fortunately, neither interference is very large. Using polarization filters and Stokes laser bandwidths of modest breadth ($\sim$ 130 cm^{-1}), interference-free CARS spectra from flame N_2 can be obtained even at high soot densities.

CARS signatures from N_2 have been employed to map the temperature field with high spatial precision throughout a small, luminous, highly sooting, laminar propane diffusion flame. The CARS signatures were monitored and averaged on an optical multichannel analyzer. BOXCARS (crossed-beam phase matching) was employed at angles which provided a cylindrical measurement volume 0.4 mm in diameter by approximately 1 mm long. A coannular burner was employed. Propane issued from the central tube, 1.27 cm dia. surrounded by an air flow from the outer 2.54 cm dia. tube. The air was swirled slightly to promote better spatial stability of the flame. Axial and radial profiles at five axial locations of temperature were obtained by fitting the experimental spectra with computer synthesized spectra. Such a procedure in clean flames produced measurements which agreed with radiation corrected thermocouples to within 50 K. The temperature profiles (Refs.1,4) are quite interesting and quite illustrative of diffusion flame behavior.

By using very high mass flow rates, a highly swirled turbulent diffusion flame could be produced on the coannular burner. In one series of experiments, CARS was generated from room air and the effect of placing the swirled flame in various combinations of the input beams used to generate CARS was studied. With all three input beams passing through the flame, reductions in CARS generating efficiency up to 15% were noted. In a second series of tests, single pulse ($\sim$10 nanosecond) CARS N_2 spectra captured on the optical multichannel analyzer were obtained from various regions of the swirled flame. The spectra are of fairly high quality and demonstrate the feasibility of CARS, albeit on a small scale, for turbulent flame diagnostics. Based upon these investigations CARS continues to appear very promising for application to practical combustion sources. A logical next step in CARS development would be a program of full scale combustor testing.

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LASER RAMAN PROBE FOR COMBUSTION DIAGNOSTICS

General Electric Company, Corporate Research and Development
Schenectady, New York
Subcontract No. 8960-17

M. Lapp, Principal Investigator
C. M. Penney, Physicist
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Introduction

The current objective of this effort is to measure simultaneously the fluctuation values of flame temperature and product gas density, using spontaneous Raman scattering, and axial flow velocity, using laser velocimetry, for a turbulent diffusion flame. This effort has been undertaken in order to utilize these optically compatable probes in a significant fluid mechanic investigation designed to produce probability distribution functions (i.e., histograms) and correlations of these properties. This work was interrupted during the initial phase of this contract period because the optical light scattering/combustion laboratory became inoperative due to a malfunction of a key piece of equipment, the pulsed dye laser source for Raman diagnostics.

Discussion

The untimely disturbance to the operation of our laboratory during most of this reporting period has prevented us from achieving our goals on time. We have taken the opportunity, while the laboratory was not operating, of redesigning our facility. According to our current timetable, all critical parts of our refurbished system will be on hand by April, and the diagnostic facility will be operated as soon as feasible following this. Some key elements are already in place and undergoing tests. A no-cost extension of this contract will provide us with adequate time to finish our objectives.

The new laboratory facility will contain significantly improved equipment, including a new combustor, new laser source, and refurbished optical detection equipment. A turbulent diffusion flame of the same character as that produced in our previously-used fan-forced combustor will now be generated in a larger fan-induced square-cross-section turbulent combustion tunnel. This apparatus, presently being completed at Aerolab Corp., Laurel, MD, is designed to have a very low initial turbulence level as well as excellent optical access.

The new state-of-the-art dye laser source, manufactured by Candella Corp., Natick, MA, is designed to produce 1 J/s pulses for up to 1 hour before dye replenishedment is required. It has arrived recently, and preliminary assembly and testing has indicated sound design and operation.

Three areas of effort on this contract were addressed during the portion of the reporting period that work could be accomplished. First, additional experience was gained in the acquisition of simultaneous axial velocity and gas temperature data, and in the most illuminating ways to present these data. Secondly, based upon this experience with our vibrational Raman scattering (RS) and laser velocimetry (LV) probes, we explored a realignment of the LV system to make the probed test volume for these two diagnostic methods more nearly coincident. Our first configuration placed the RS and LV volumes (both, very roughly, of cylindrical shape) with their major axes orthogonal. The new arrangement makes their major axes coincident.

The third area of effort was the preliminary spectral set-up and alignment of the spectrometer-detector system to be used for fluctuation temperature and product gas density measurements. The temperature for the H_2-air turbulent diffusion flame experiments is determined from vibrational RS Stokes/anti-Stokes intensity ratios from N_2; the H_2O vapor product gas density is to be monitored from its vibrational RS signature through use of an additional photomultiplier channel (i.e., additional to the two used for the Stokes and anti-Stokes N_2 signals) in the polychromator housing attached to the 3/4-m high-aperture SPEX Model 1800 spectrometer used for optical discrimination. Because of the large opening in the exit plane of this instrument (created to facilitate photographic plate recording), sufficient space exists to measure simultaneously Raman signals as far apart spectrally as (for 488 nm excitation) the N_2 anti-Stokes vibrational Q-branch at 438 nm and the H_2O vapor Stokes Q-branch at 594 nm.

Notes and References

Recent publications and manuscripts related to this research effort supported by Project SQUID and by other parallel General Electric and government efforts are listed below:

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AN EXPERIMENTAL STUDY OF

REACTIVE AND NONREACTIVE FLOWS

IN A JET AND CHANNEL

Polytechnic Institute of New York
Aerodynamics Laboratories

Subcontract No. 8960-5

S. Lederman - Principal Investigator

Introduction

In the last semiannual report of October 1, 1978, it was indicated that an attempt has been made to compare the data obtained in our laboratory, using the single Q-switched laser pulse spontaneous Raman diagnostic and the LDV techniques with the data obtained on similar jets and flames in other laboratories, which are utilizing the conventional diagnostics. In this current period, this work has been expanded with the introduction of a new laser system. With the higher pulse repetition rate of the new laser, data such as the probability density functions are now extracted from the Raman and LDV systems.

Discussion

As has been pointed out in the preceding semiannual report and discussed in References 1-9, the applicability of the spontaneous Raman effect to the nonintrusive diagnostics of flow fields encountered in combustion and propulsion represented a major part of the development effort in our own and many other laboratories for the last several years. More recently after acquiring some confidence in the new techniques, attempts were made to compare experimental data obtained using those techniques with data obtained on similar experimental configurations using conventional measurement techniques (References 10-16). It has been shown in Reference 17 that our velocity data in similar cold jets and flames agree well with the data of several investigators, the concentration of species however agreed only on cold jets. In flames the concentrations measured differed markedly. Considering the fact that in our own case the concentrations were measured using the Raman effect in both cases, cold jet and flame, and in the other laboratories chromatography was generally used, with its inherent intrusive interference, it appears that more credence should be given to a remote nonintrusive technique.

Based on this in the present reporting period, more data are

being acquired on an air CO_2 methane flame. In addition, in view of the importance of the PDPF's in modeling turbulent combusion phenomena, the histogram of the concentrations and temperature of the flame as well as the velocity histograms are being retrieved from the data acquired. Several examples of the histograms are shown in Figures 1 and 2.

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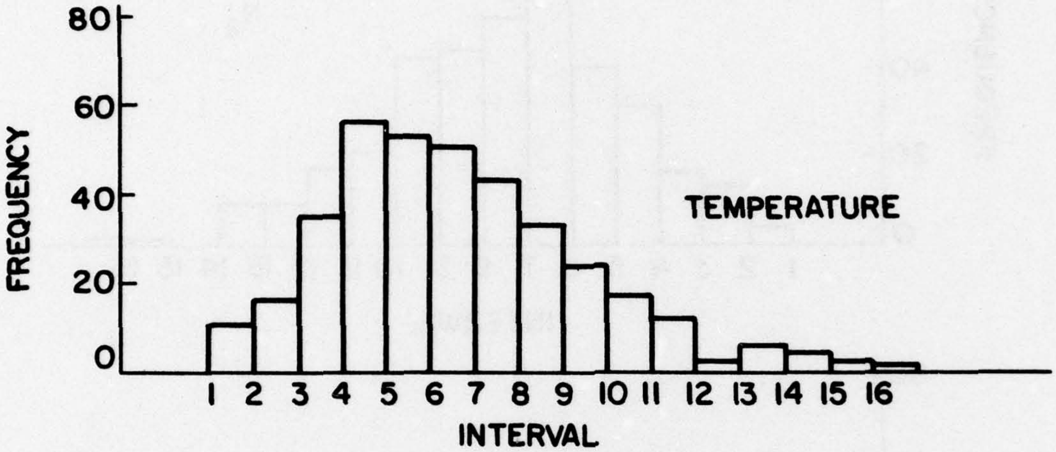
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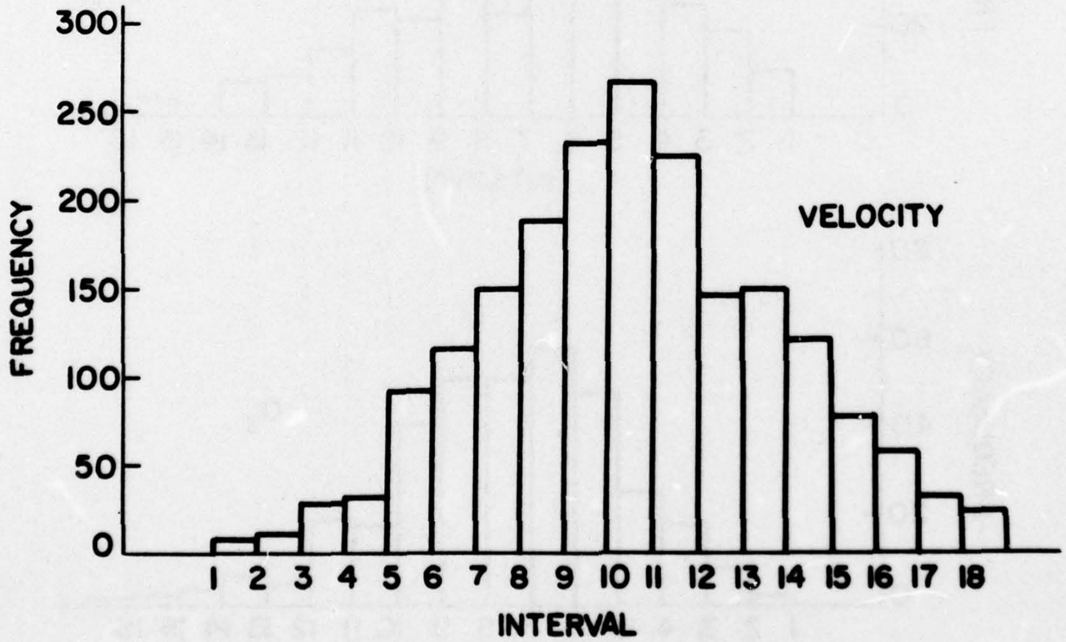
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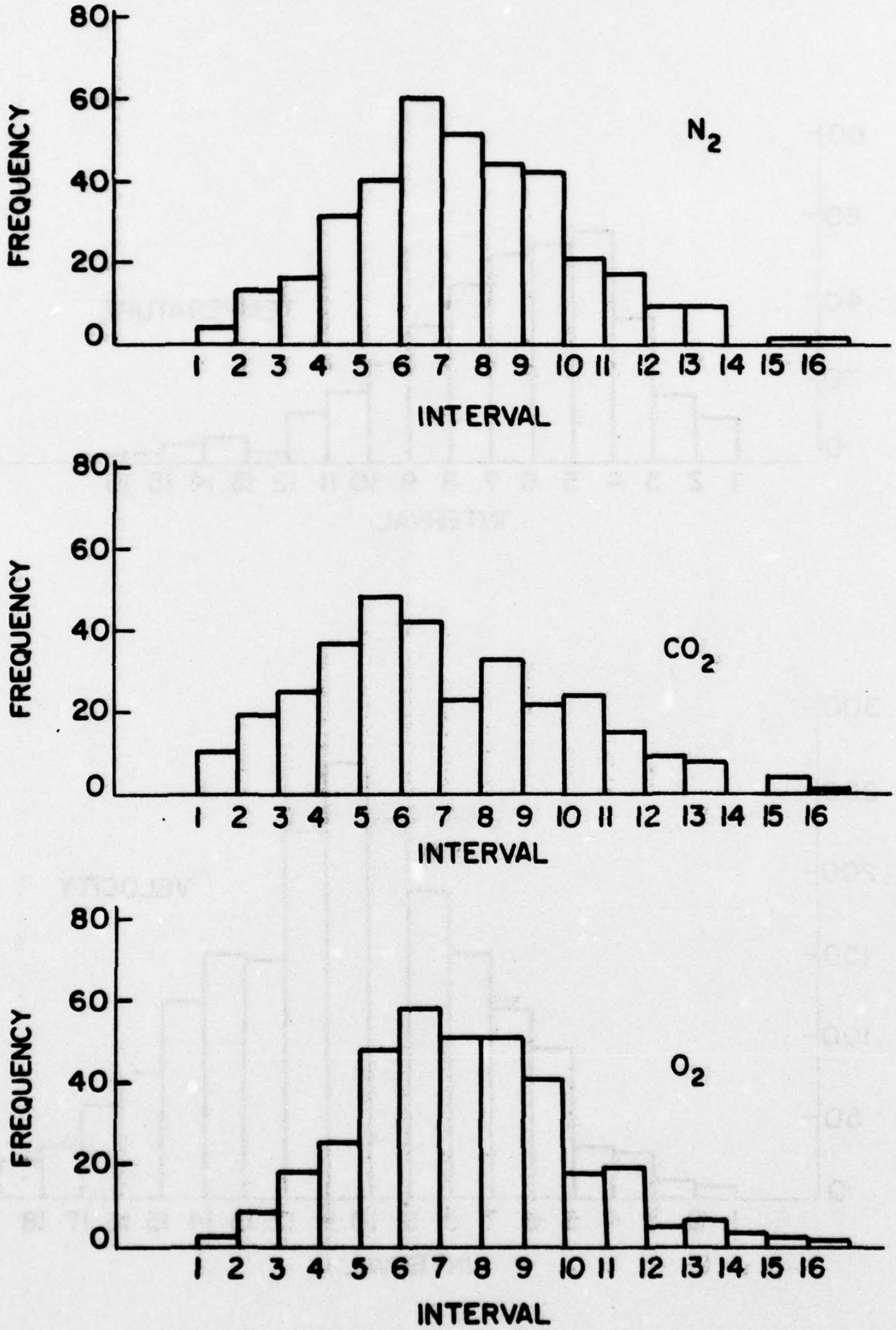
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IV. TURBULENCE

Semi-Annual Progress Report

LARGE-SCALE STRUCTURE INTERACTIONS IN A TWO-DIMENSIONAL TURBULENT MIXING-LAYER

Subcontract No. 8960-12

Professor F.K.Browand, Principal Investigator
Dr. B.O.Latigo, Research Associate

Introduction

The existence of fairly well organized, quasi two-dimensional large-scale vortical structures (LSS) within the two-dimensional mixing layer is now well documented over the Reynolds number range 10^3-10^7. LSS features similar to the above have also been recorded at Reynolds numbers above 10^{10} on the Jovian atmosphere by the Voyager 1 spacecraft. Thus, the LSS appear to be a characteristic feature of turbulent flows, hence the interest. The present controlled experiment is conducted in a wind tunnel at Reynolds numbers of 10^6 in order to evaluate the importance of these LSS interactions to the dynamics of a turbulent mixing region.

Discussion

A complete analysis and interpretation of the conditional u and v velocity measurements reported in the last progress report has been completed and the findings are reported in the one reference cited at the end of this report, and also in the version currently being prepared for publication.

The dynamical importance of the LSS is obtained by studying the perturbation velocity ensembles u_e, v_e, and the LSS momentum flux $u_e v_e$, across the flow at several x-stations. Using data at x=30 in., which corresponds to the final stages of a high Reynolds number pairing interaction between the initial four vortices mentioned in the last progress report, it is shown that the LSS stresses $(\overline{u_e^2})^{1/2}$, $(\overline{v_e^2})^{1/2}$, and $\overline{u_e v_e}$ contribute about 50% of the respective long-time Reynolds stresses. This result is shown in Figures 1 and 2. Mean values are evaluated over the local LSS passage period. The other 50% contribution comes from background turbulence.

As was shown previously, the LSS momentum flux is predominantly positive over a typical LSS passage period. Instantaneously very high and positive $u_e v_e$ flux was seen towards the low-speed edge of the mixing region indicating an upward transport of high momentum fluid. High and negative $u_e v_e$ flux is never seen. To obtain a visual picture of the flow at each x-station from the measurements, ensembles U_e, V_e of the

instantaneous velocities u and v respectively, instead of ensembles u_e and v_e, are used to construct velocity-vectors (or streamlines). Such a picture is presented in Figure 3 for the furthest measurement station x=38 in., at which time just one vortex structure resulting from previous pairings remains in the flow. In the above figure, the Eulerian measurements are transformed into a Lagrangian system for an observer moving with the LSS of centerline convection velocity $U_0=(U_1+U_2)/2$, and mean centerline lateral velocity V_0. To this observer the high-speed stream (bottom) appears to convect downstream at a velocity U_1-U_0, while the low-speed stream (top) convects upstream at a velocity U_0-U_2. At the same time, the LSS induced momentum transport appears to be symmetric - entrainment of high-momentum fluid ahead of the LSS and an equal but opposite entrainment of low-momentum fluid behind the vortex structure. One additional feature of interest arising out of this study is that the LSS pairing interactions take place over a wide Reynolds number range.

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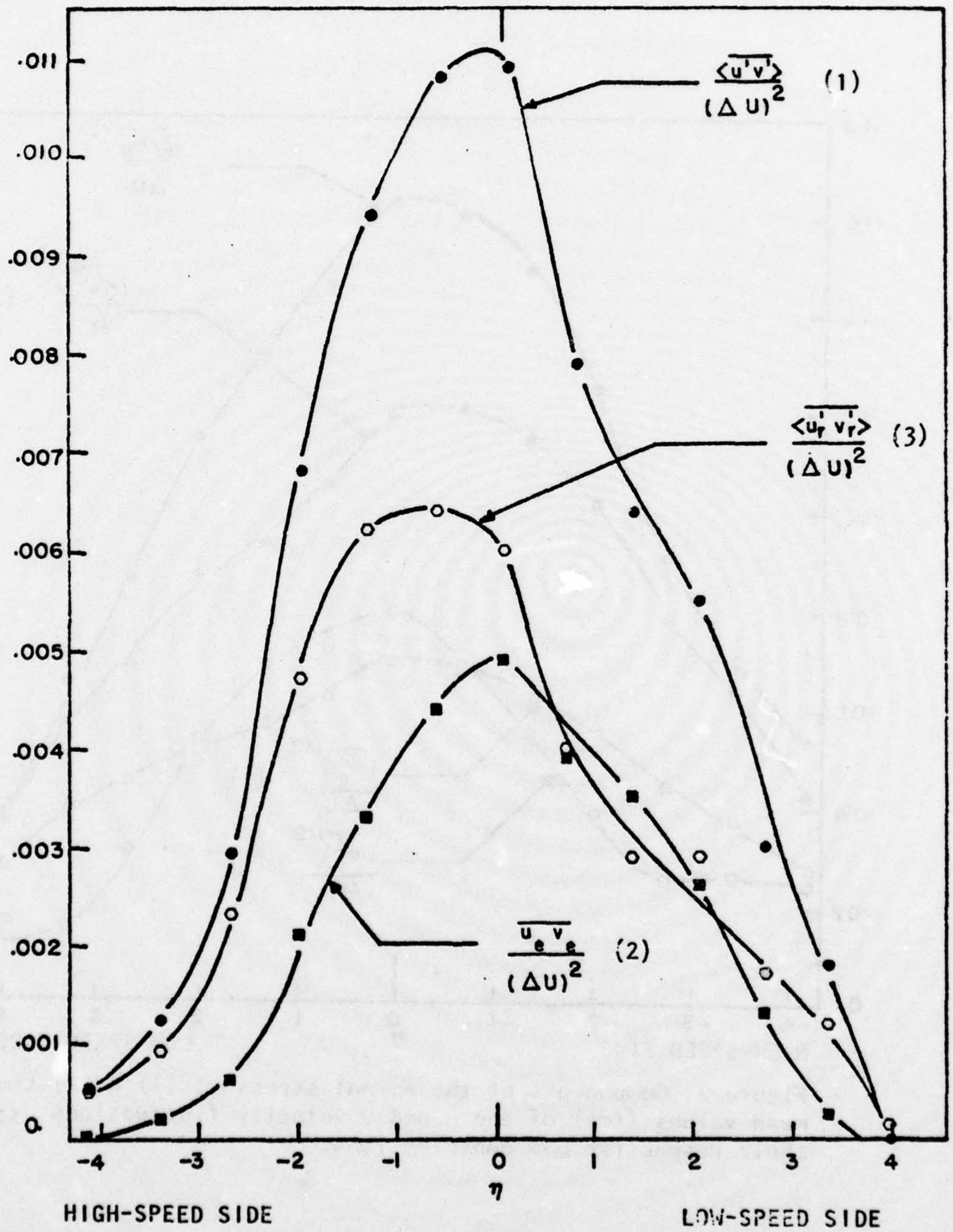

Figure 1. Components of the Reynolds stress. (1) Long-time mean value: (2) LSS contribution: (3) Background turbulence contribution.

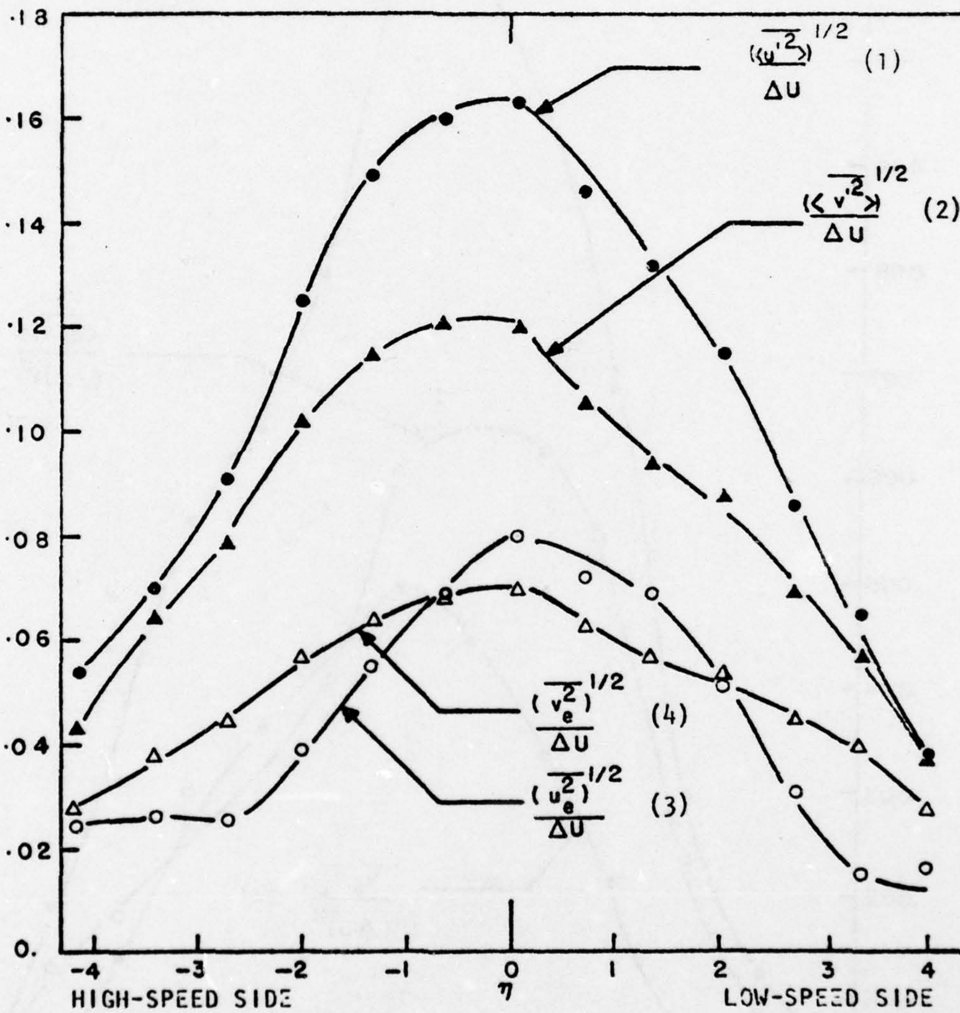

Figure 2. Components of the normal stresses. (1) & (2) Long-time mean values (rms) of the u and v velocity fluctuations. (3) & (4) their respective LSS contributions.

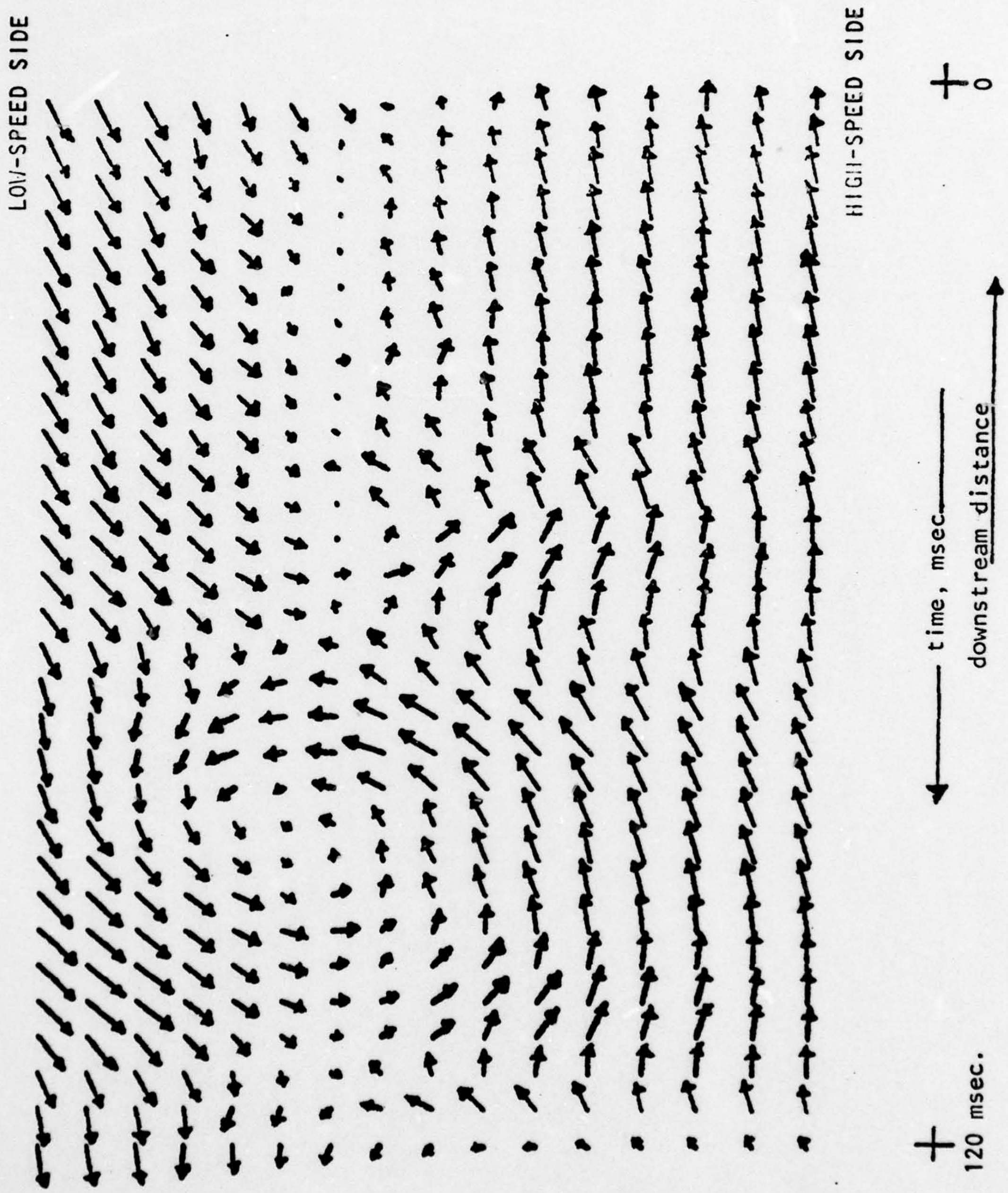

Figure 3. Velocity-vector plots of (U_e, V_e) with time at several positions across the mixing region for an observer moving with the LSS of centerline velocity (U_0, V_0).

Semi-Annual Progress Report

THE STRUCTURE OF EDDIES IN TURBULENT FLAMES

University of Sheffield, England
Subcontract No. 8960-30

Dr. N. A. Chigier, Principal Investigator
Dr. A. J. Yule, Research Fellow

Introduction

This investigation has the objectives of measuring the structure of turbulent flames and identifying and quantifying the roles of the large eddies in these flames. It is intended to achieve an improved fundamental understanding of the mechanics of turbulent combustion. Previous experiments have shown that large coherent eddies are found in non-reacting shear flows and there are many indications that similar structures exist in various types of combustor. These eddies have a strong influence on mixing, as well as the other important characteristics of turbulence; it is essential that their physical structures are understood in order to permit improved modeling of turbulent combustion. An experimental investigation is being conducted to determine the fundamental structures in axisymmetric gas diffusion flames. Initially, work is being concentrated on the transition region of a jet flame, where vortex formation is clearly visible.

Discussion

Further developments have been made in the range of high frequency response measurement techniques that are being designed and tested specifically for measurement of large eddy structure and coherence in flames. Flow conditions have been achieved providing well-controlled, low turbulence initial conditions at the burner so that the flame develops naturally from a laminar nozzle boundary layer. Direct comparisons are being made between measurements made under burning and nonburning conditions.

The transitional flame structure has been found to be physically similar for both cold and burning flows; vortex ring formation, coalescence and eventual three-dimensional breakdown into turbulent flow have been found. High-speed colour Schlieren movie films show that burning in the transitional flame occurs in quasi-laminar interface layers which are distorted, stretched and convoluted by the vortex interaction. These distortions control local interface burning characteristics and, thus, local flame luminosity. Visualization by Schlieren techniques shows the axisymmetric wave and vortex ring formation much more clearly than direct photography. Reaction in the transitional flame is found to be localized at, and controlled by, the interface corresponding to the vortex sheet shed at the nozzle. Heat released by reaction is found to have a strong influence on the dynamics of these interface layers and, hence, on the associated vortex ring dynamics. Point measurements of velocity, temperature and ionization density show that the transitional flow, and also the potential core of the jet, are very much longer in the flame than in the non-burning jet. However, there is a marked difference between the initial fundamental instability frequencies of the shear layers for the burning and nonburning flows; the cold case is in good agreement with the most amplified frequency predicted by stability theory for cold inviscid flow. Reaction appears to manifest itself most strongly in delaying and damping the processes of vortex formation and coalescence. Increased viscosity, due to temperature increase, appears to be the major effect but dilatation and buoyancy forces also contribute to the observed phenomena.

In the transitional flow, the dominating roles of large-scale, vortex structures have been clearly shown by their effect on determining mixing and burning in quasi-laminar interface layers. It remains to be shown the extent to which these observations can be extended to the fully turbulent flame further downstream. On the basis of the flow visualizations and measurements made in the present investigation, coupled with data from previous investigations on cold jets, it is concluded that large eddies play an important role in the initial transitional region of turbulent jet flames.

During the current reporting period, modification has been made to the burner and traversing mechanisms; new versions of the ionization probe have been constructed and tested; the signal processing for the laser anemometer has been redesigned, constructed and tested. Recording and analysis of data has undergone, and will continue to undergo, significant development changes. A new 32 K memory microprocessor has been ordered; the ultimate aim is to have the complete data analysis system entirely integrated with the experimental equipment with the capability of making direct correlations between velocity and temperature and also carrying out conditional sampling.

Detailed measurements with a hot wire anemometer have been completed for the cold flow conditions. These allow complete specification of the initial flow conditions, including boundary

layer thicknesses on inner and outer walls of nozzles and turbulence levels in the primary and secondary flows. The hot wire anemometer is also used to obtain frequency spectra in the mixing layer region of the jet. Initial problems with signals from the ionization probe have been overcome and spectra based upon ionization probe measurements have been compared directly with hot wire data.

The high-speed camera has been used for direct photography of the flame and also for colour Schlieren photography. Frame-by-frame analysis of these films has provided data on passing frequencies and separation distances of individual eddies. The detailed physical structure of the flow and flame is being deduced from close examination of these films.

A comprehensive Technical Report has been written and is in the final stages of preparation. This report discusses at length the overall objectives and philosophy of approach for the determination of the structure of turbulent flames. The measurement techniques, signal processing and data analysis by computer are described in detail. The framework, notation and techniques for data handling, analysis and presentation are described for ensemble averaging, conditional sampling and determination of eddy structure from multiple probes. Results are presented of photographic studies, amplitude spectra, time-averaged, rms and pdf distributions for velocity and temperature.

A paper[1] was presented at the AIAA Seventeenth Aerospace Sciences Meeting by Dr. Chigier. Dr. Yule is preparing a paper for presentation at the Shear Flow Conference in London in July 1979.[2]

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Semi-Annual Progress Report

HETEROGENEOUS TURBULENT FLOWS RELATED TO PROPULSIVE DEVICES

University of California, San Diego
Subcontract No. 4965-26

Paul A. Libby
Principal Investigator

Introduction

This research addresses problems related to the turbulent heterogeneous flows which arise in a variety of propulsive devices when reactants and products mix and react. The effort is both experimental and theoretical; the experimental program concerns exploitation and extension of the multiple sensor "hot wire" technique of Way and Libby which permits time-resolved and space-resolved measurements of velocity and concentration of one light species, e.g., helium, in a mixture of light and heavy gases under isothermal conditions. The application of this technique in the present research is to a confined internal flow corresponding to an idealized combustor. The related theoretical work supports the experimental effort and attempts to extend the results thereof to flow situations of more practical concern, e.g., to chemically reacting flows.

Discussion

Our theoretical work continues to be concerned with turbulent flames in premixed reactants. In our previous Semi-Annual Progress Report we discussed our interest in developing a theory for such flames free of the usual gradient approximation. There are two motivations for pursuing such a theory. First, it will permit analysis of the influence of acceleration on the behaviour of turbulent flames and will provide an independent assessment of the validity of gradient transport under the severe conditions existing in turbulent flames with significant heat release. We also pointed out in our previous Report that simple physical ideas based on the laminar flamelet model of the reaction zone establish a new model for the dissipation of fluctuations of product concentration, an important quantity in the theory of

such zones. In the past few months those same ideas have been applied to reexamine several other dissipative terms appearing in the conservation equations. Of particular interest is the cross-dissipation involving the product of gradients of product concentration and gradients of velocity. This dissipation is generally neglected in non-reacting flows on the grounds of local isotropy. However, the laminar flamelet model relates this dissipation to the rate of production of product i.e., to a direct chemical effect.

We use this new model for the cross-dissipation in our new non-gradient theory which we apply to turbulent flames normal to the oncoming stream. In such flames the only flux of interest is in Favre averages, $\overline{\rho u''c''}$. In the gradient transport this is algebraically related to $-d\tilde{c}/dx$ where $\tilde{c}$ is the Favre-averaged, mean product concentration. In the new theory a conservation equation for this flux is considered with the consequence that there are a variety of effects influencing $\overline{\rho u''c''}$ not explicitly or implicitly taken into account in gradient transport theories; thus, in the present calculation the effects of convection, diffusion, production by three different mechanisms including a chemistry effect, and the cross-dissipation mentioned earlier on one of the two principal variables $F \alpha \overline{\rho u''c''}$ are accounted for. The second dependent variable is the intensity of the velocity fluctuations, $I \alpha \overline{\rho u''^2}$. Although there are various approaches possible, we have chosen one of the eigenvalues to be determined as part of the solution to be the ratio I^{∞}/I_o, i.e., the ratio of the intensity of the velocity fluctuations downstream of the reaction zone to the intensity in the approaching stream. A second eigenvalue is the coefficient multiplying the cross-dissipation term. This choice assures that the turbulent flame speed is in accord with the predominant experimental results. The calculations are done in terms the mean product concentration $\tilde{c}$.

We show in Figure 1 and 2 the distributions with $\tilde{c}$ of three different determinations of F for two different values of the heat release parameter τ. We see for $\tau = 1$ which corresponds to a value for the temperature ratio $T_{\infty}/T_o = 2$ that the gradient theory, and the non-gradient theory with and without the pressure gradient effect taken into account yield qualitatively the same fluxes, i.e., negative values of F in accord with gradient transport. Figure 2 yields the same distributions for a somewhat greater degree of heat release, namely $\tau = 2$. In this case the effect of pressure gradient become crucial and results in $F > 0$, i.e., to countergradients of product. By computing the distributions of the main contributors to the balance of F, we find that as the heat release increases the pressure gardient term behaves essential as $\tau^2 \tilde{c}(1 - \tilde{c})/(1 + \tau\tilde{c})$, independent of the two dependent variables. As a consequence the pressure term drives the solutions and results in the countergradients shown.

This result has important implications for the modelling of fluxes not only in turbulent reacting flows but in any turbulent flows with significant heterogenieties in density, e.g., in the mixing of helium and air. Our plans for the near future relative

to this theoretical effort are to exploit and to develop further the new theory and to apply it to the determination of the effect of acceleration on normal turbulent flames.

The data reduction of the experiment described in our previous Progress Report, namely that involving a two-dimensional jet of heated helium discharging into a moving airstream, has been largely completed. Some of the data indicate excellent quality; e.g., the mean distributions of velocity, helium concentration and temperature are symmetric about the horizontal centerline of the jet. However, the intensities at the upstream stations indicate an assymetry about that centerline although they appear to be evolving properly with streamwise distance. The data for the most downstream station has as yet not been fully analyzed. Thus the complete success of the experiment is not as yet established.

One result of considerable interest obtained from a preliminary analysis of one interface passage is shown in Figure 3. The distributions with time of the temperature and helium concentration variations through an interface are shown. We see that the concentration interface is significantly thicker than the temperature interface; this result which is new is in accord with the notions that the superlayer thickness depends on either of the Schmidt and Prandtl number as appropriate. Since these numbers differ by a factor of three for dilute mixtures of helium and air, the observed distributions are considered verification of this important notion.

At the present time we continue with the analysis of our test results and shall prepare one or more manuscripts for publication.

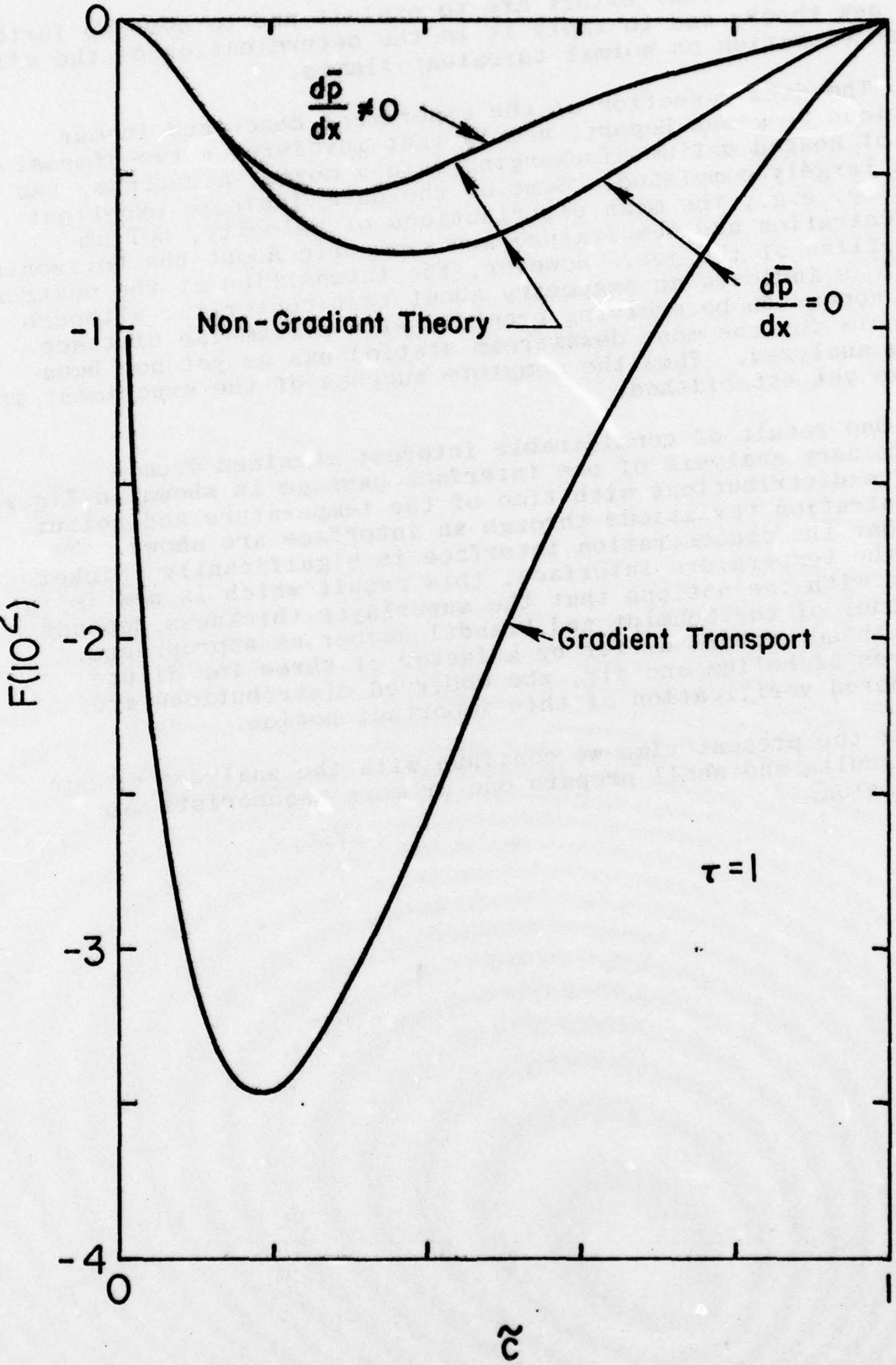

FIGURE 1: Distribution of mean product flux through a normal turbulent flame: τ = 1.

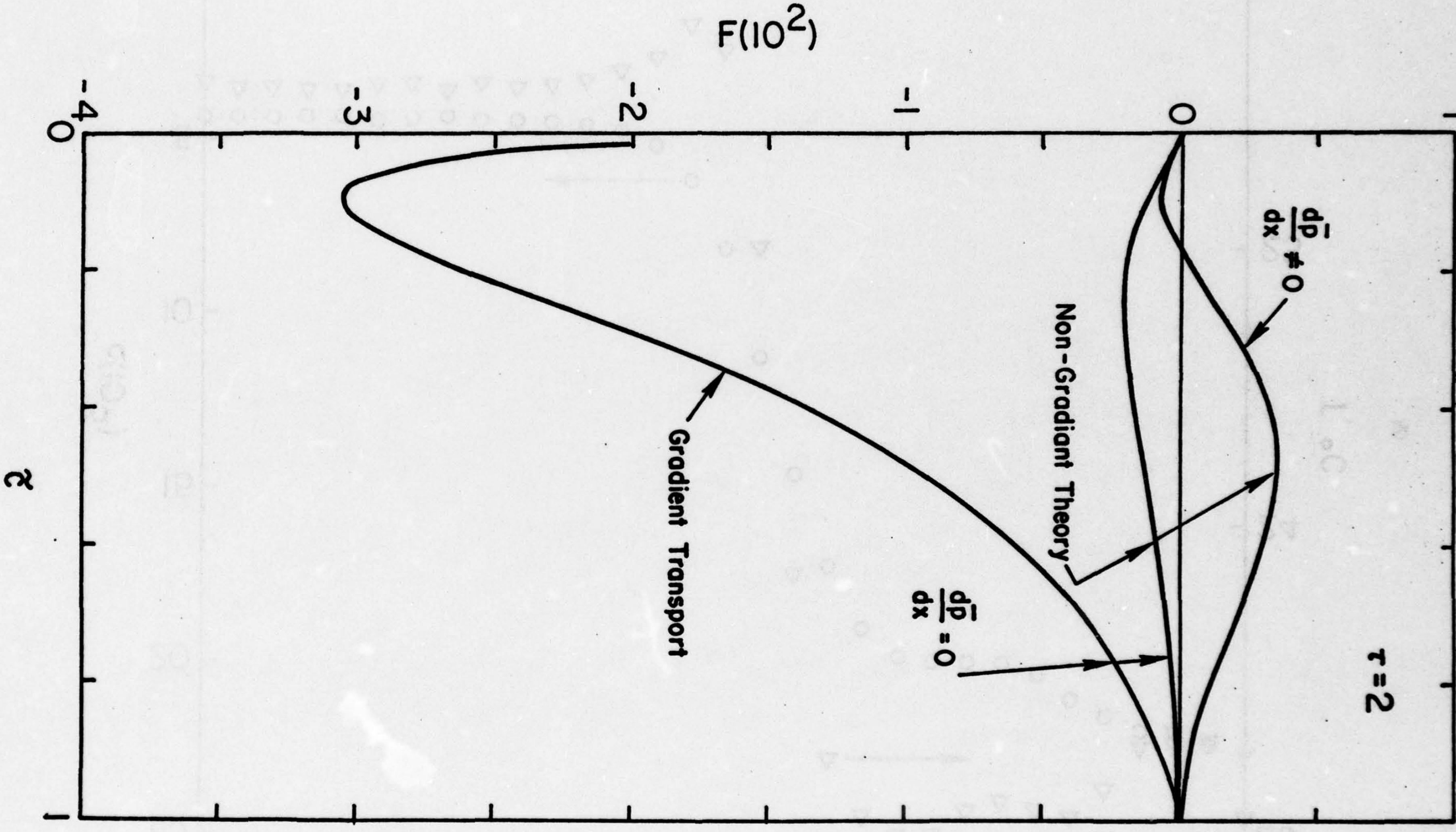

FIGURE 2: Distribution of mean product flux through a normal turbulent flame: $\tau = 2$.

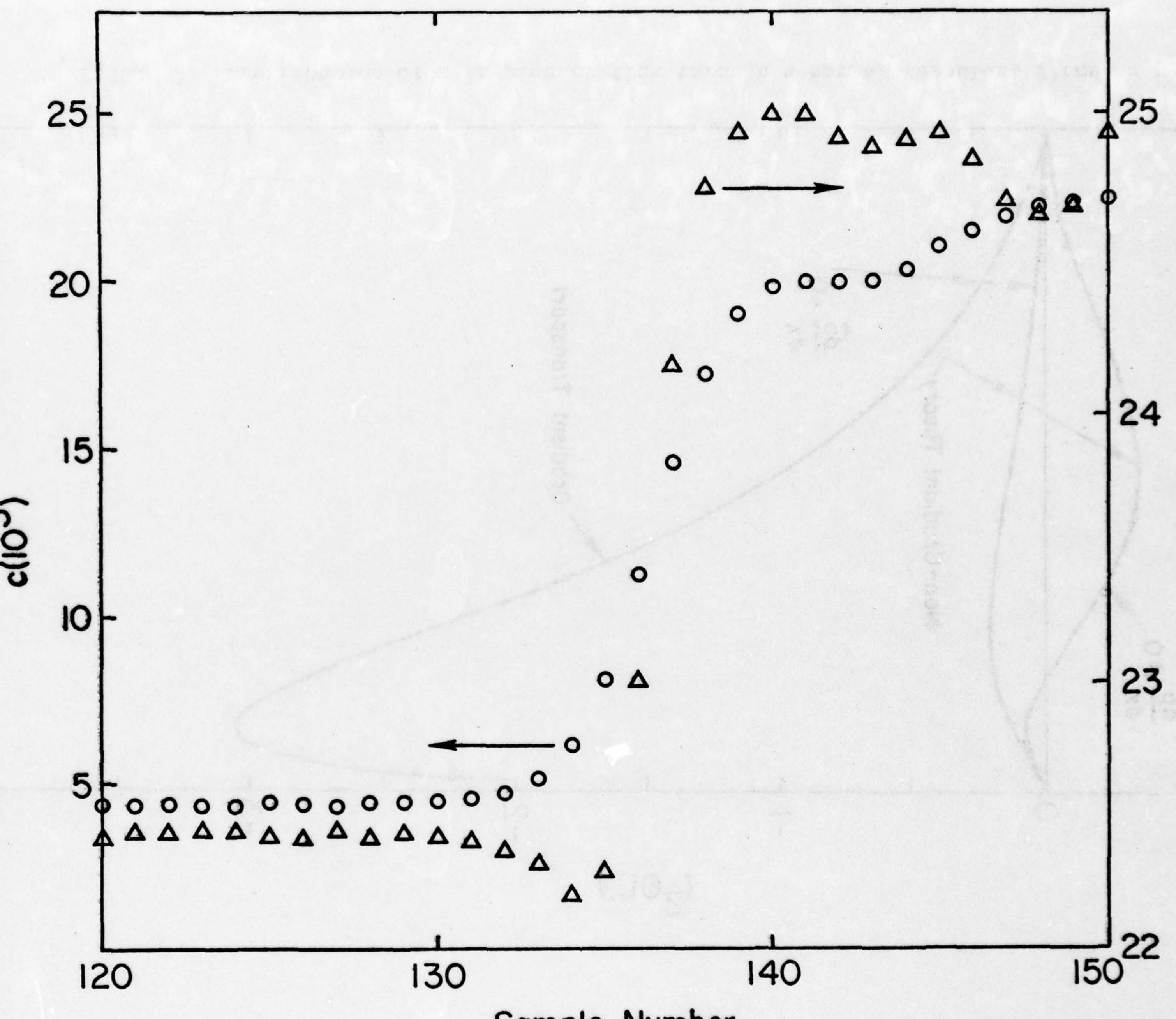

FIGURE 3: Distributions of temperature and helium concentration through the superlayer.

RESEARCH ON TURBULENT MIXING

California Institute of Technology, Pasadena, California
Subcontract No. 8960-1

Professor A. Roshko, Principal Investigator
Prof. P. E. Dimotakis, Co-Investigator
Mr. Luis P. Bernal, Research Assistant
Mr. Daniel B. Lang, Research Assistant

Introduction

The objective of this research is to obtain a better understanding of the turbulent mixing processes that occur in mixing layers between gas streams of different velocities and densities. Such mixing layers are often a basic element in flows which occur in propulsive devices; examples of problems to which the research is relevant include turbulent combustion, jet noise, and thrust augmentation. The research has proceeded along two parallel lines. On the one hand, we have been making measurements of various statistical properties of the mixing region and their dependence on parameters such as Reynolds number, velocity ratio and density ratio. Such information provides important inputs for engineering models and calculation methods. On the other hand, we have been using the quantitative measurements, e. g., time- and space-resolved concentration measurements, together with flow visualization to identify and describe the physical processes occuring in such mixing regions. Better understanding of the physics is important for the development of more realistic computing models and also for suggesting how turbulent mixing might be controlled or modified.

An important development occurred several years ago when it was discovered that turbulent mixing layers are dominated by large, organized, quasi-two-dimensional vortices or rollers, whose evolution and interactions dominate the development of the layer and control the gross mixing or engulfment of fluid from the two sides of the layer. Of course, turbulent flow could not be strictly two dimensional at high Reynolds number, but there has been considerable controversy as to how the three dimensionality develops. One school (Ref. 1) holds that

there will be a complete "breakdown" of any organized structures. Our own views, based on theexperience of this laboratory (Refs. 2, 3, 4) and others, is that the existence of the organized structures has been demonstrated up to very high Reynolds numbers, that the tendency to organize characteristic structures is a basic property of the underlying mean vorticity distribution, and that the important three dimensional development is that of secondary and smaller scale motions superimposed on the main large ones. In Refs. 3 and 4 it was shown that no significant change in the large structure and in the gross development of the flow occurs when smaller scale structure develops at increasing Reynolds number. The amount of fluid engulfed is not appreciably changed. The main result is to increase the internal mixing, i. e., the extent to which the intimate molecular mixing is completed. Larger spanwise irregularities and departures from two dimensionality also occur to some degree but it does not appear that these make a major contribution to the mixing at either the large scale or the small scale. A further finding in previous work on this contract was that the enhanced internal mixing is related to the appearance (in plan view of the mixing layer) of a pattern of streamwise streaks which have a fairly spanwise regular spacing (see figures in our previous reports in this series).

Discussion

One of the purposes of our present research program is to put the above observations on a firmer basis quantitatively. Some progress has been made in a parametric study of the streak patterns which appear in plan view pictures of the mixing layer; the streaks are thought to delineate secondary instabilities which produce streamwise vorticity, i. e., the first manifestations of three dimensionality and of the vortex stretching required for dissipation at increasing Reynolds number. The picture also suggests a further instability and breakdown of these streamwise streak patterns to smaller scales; the streamwise position at which this occurs corresponds to the position where the increase in internal mixing was observed by Konrad (Ref. 4). Experimental findings that have been obtained since our last report include the following.

The spanwise spacing of the streaks is found to be related to the initial streamwise spacing of the main vortex structures, i. e., to the wave length of the initial Kelvin-Helmholtz instability wave. In fact, the ratio of these spacings is found to be unity, within the experimental uncertainty. Thus the streaks are associated with a secondary instability originating in the amplified Kelvin-Helmholtz waves (i. e., the first organized rollers). What is remarkable is that the streaks persist, at the same spacing, downstream even after several pairings of these rollers have occurred. As reported earlier, the streak spacing eventually does increase with downstream distance, apparently accommodating to the increased scale (thickness) of the mixing layer.

High speed Schlieren movies which have been obtained show simultaneous edge and plan views of the mixing layer with concentration probes in place, making it possible to see how the instantaneous probe signals relate to the turbulent structure (rollers seen in side view, streaks seen in plan view) which is visualized on the movies. These relationships are being studied.

Simultaneous measurements of the concentration from two probes deployed spanwise tend to support our view that the spanwise streaks are associated with longitudinal, counter rotating vortices. Figure 1 shows conceptually how two pairs of vortices might look in a cross-sectional view looking streamwise in the mixing layer between streams of He and N_2. Between one pair N_2 would be strongly entrained into the mixing layer by the counter rotational action while between another pair He would be entrained. From the simultaneous observations of probe outputs and movies it is found that the bright streaks (Fig. 1) correspond to the position where N_2 is strongly entrained. At those positions the mean value of helium concentration $\overline{X}_i$ is lower than at positions halfway between, as shown in the plot of Figure 1. Also shown there are measurements of the correlation $\overline{X'_i X'_j}$ between the concentration fluctuation X' at two points i and j, respectively. With i at the position of a bright streak and j at the adjacent one the correlation is quite high (0. 7) but when j is moved <u>closer</u> (halfway) to i the correlation <u>decreases</u>. This also lends support to the view that the streaks are associated with streamwise, counter rotating vortices.

This work was reported (Ref. 5) at the 31st Meeting of the APS Division of Fluid Dynamics at the University of Southern California, 19-21 November, 1978. A more comprehensive account has been accepted for presentation at the forthcoming Second Symposium on Turbulent Shear Flows (Ref. 6).

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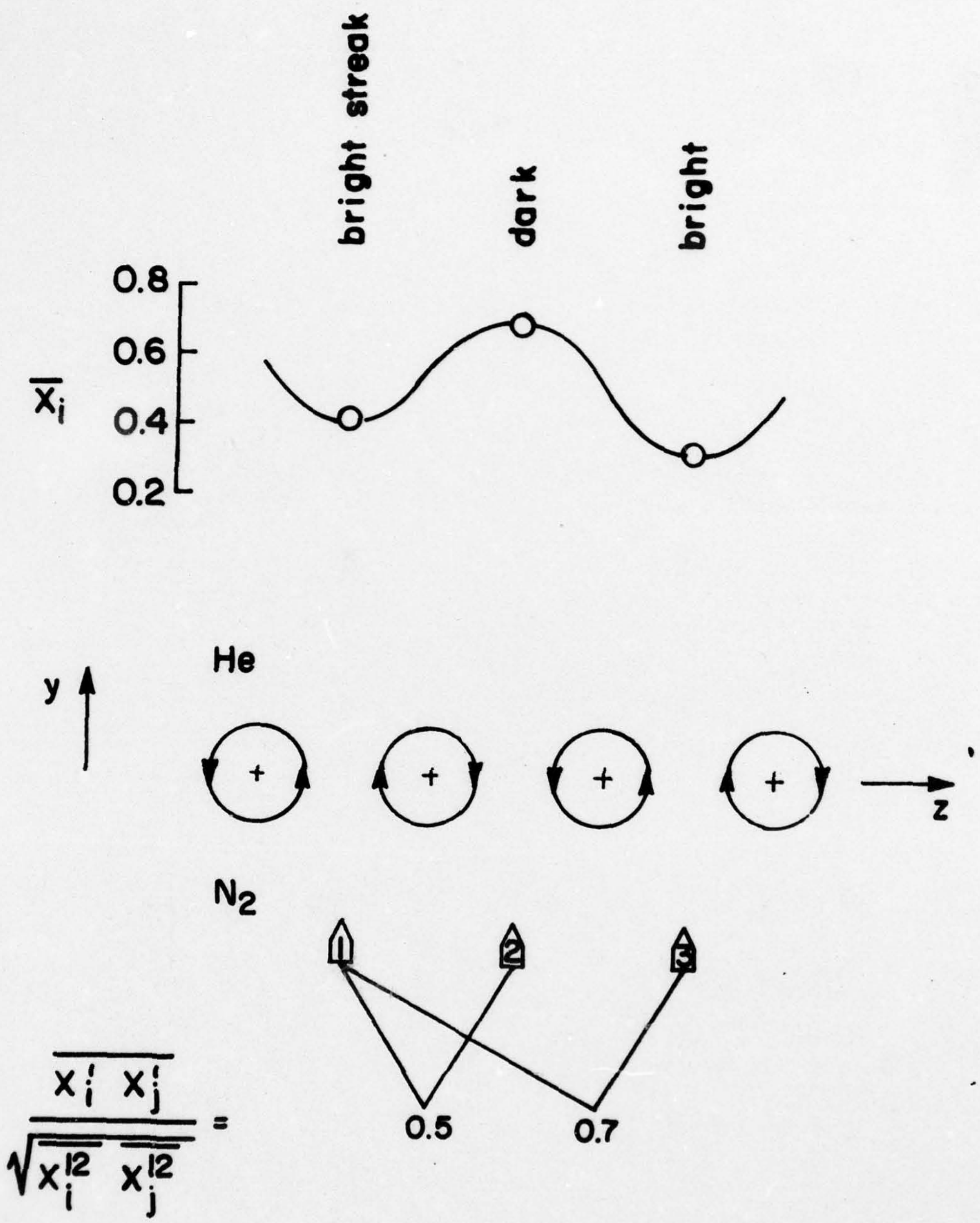

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bright
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0.4
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$\overline{X_i}$
He
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$\frac{\overline{X_i' \; X_j'}}{\sqrt{\overline{X_i'^2} \; \overline{X_j'^2}}} =$
0.5
0.7

Figure 1

SWIRLING HEATED TURBULENT FLOWS AS RELATED TO COMBUSTION CHAMBERS

University of Colorado, Boulder, Colorado

Professor M. S. Uberoi, Principal Investigator

Experimental results, general stability, and dynamical considerations show that turbulent line vortices can not exist except for an initial disturbance which decays and cannot be sustained. Published theories are based on untenable hypotheses for a nonexistent turbulent flow (1).

We have completed analysis of the axial flow in trailing line vortices. The errors and omissions in previous work of others have been removed (2).

The development of the theory for the decay of laminar and turbulent vortices is completed. The theory critically examines other published theories and shows that the mechanisms proposed by us are more tenable than those proposed earlier by other investigators (3).

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SECOND-ORDER CLOSURE MODELING OF TURBULENT COMBUSTION

Aeronautical Research Associates of Princeton, Inc.
Princeton, New Jersey
Subcontract No. 8960-26

Ashok K. Varma, Principal Investigator

Introduction

Turbulent flows involving chemical reactions are a basic feature of many combustion and propulsion systems. The interaction between turbulence and chemistry is of considerable importance in determining combustion efficiency, pollutant formation, combustion noise, heat transfer, etc. Second-order closure modeling of turbulent reacting flows provides a convenient framework for studying these interactions between turbulence and chemical reactions, and this research program is directed toward the development of such a second-order closure procedure.

Models for the scalar probability density function (pdf) have to be developed to achieve closure of the turbulent transport equations for mixing and reacting flows. A delta function "typical eddy" model for the joint pdf of the scalar variables has been developed and incorporated in the A.R.A.P. <u>m</u>ulti<u>e</u>quation <u>t</u>urbulent <u>re</u>acting <u>c</u>ode (METREC). The pdf model has been shown (Varma et al., 1978) to provide good representations of measured pdf's in two-species, variable-density mixing flows. This progress report discusses the results obtained by complete second-order closure simulations of the variable-density mixing layer experiments of Brown and Roshko (1974) and Konrad (1976).

Discussion

The results of this phase of the research effort will be discussed in greater detail in a technical report currently in preparation.

The METREC code has been used to calculate the flowfield for Helium + Argon - Nitrogen (constant density) and Helium - Nitrogen (density ratio = 7) planar shear layers. The velocity ratio for both flows is 0.38. The calculations are started at the exit plane of the splitter plate with smooth, monotonic initial profiles of velocity and species concentrations. The initial wall boundary layers are neglected as we are mainly interested in the downstream fully developed region of the flow. A triangular profile spot of turbulence is introduced at the initial station with a peak value of $\overline{u'u'} = .01(\Delta\bar{u})^2$. Previous studies have shown that with reasonable profiles, downstream results are insensitive to the width and amplitude of the initial turbulence distribution.

Calculations have been carried out using the complete "typical eddy" pdf model including density fluctuations. For purposes of comparison calculations were also made using a pdf "model" in which third- and higher-order scalar correlations are set to zero.

Constant Density Shear Layer Studies. For nonreacting constant density flows, the transport equations do not contain any third-order scalar correlation terms. The results obtained using the two pdf models are, therefore, identical.

Predictions for the mean velocity, mean species, and species correlation profiles are compared to the Konrad (1976) data in Figure 1. The calculations used the standard A.R.A.P. model constants that have been established in the past by detailed comparison with basic incompressible jet, wake, shear layer, and flat plate boundary layer data. The calculated $\bar{u}$ profile is somewhat narrower than the experimental profile. However, the calculated $\bar{u}$ profile corresponds to a shear layer spread rate $\sigma_o = 9$. Other shear layer data show that σ_o ranges between 9 and 11. When σ_o is calculated from the Konrad data, a value of 7.5 is obtained. This is puzzling as Brown and Roshko (1974) data for air-air mixing layer shows $\sigma_o \approx 9.7$. This discrepancy has to be explained.

The differences in the mean species profiles are much larger. To match the experimental data of Konrad, it is necessary to increase the length scale model constant by 15% and to reduce the turbulent Schmidt number to 0.3 from our previous model value of 0.75 (Lewellen, 1977). The effect of these changes on the calculations is shown in Figure 2.

The change in the turbulent Schmidt number is quite large and is not supported by other comparisons with data for planar heated jets (Varma et al., 1977) and planar heated wakes (Lewellen et al., 1976). We feel additional data is required to justify model changes. The mean species profile in the Konrad data is also rather linear. Recent mean temperature measurements in a thermal mixing layer (Keffer et al., 1977) show that the profile has a characteristic error function profile. Further investigation is necessary to resolve these problems.

Variable Density Shear Layer Studies. The spread rate parameter σ_0 for the He - N_2 shear layer as calculated from Konrad data has a value of 7.4, that is, virtually the same σ_0 as for the uniform density shear layer. This does not support the conclusion of increased spreading rate for variable density flows with a high speed Helium stream configuration. The original Brown-Roshko data predicts $\sigma_0 \approx 8.8$. The differences between Konrad (1976) and Brown and Roshko (1974) data has to be clarified.

The second-order closure calculations predict mean velocity and species profiles that are significantly narrow compared to the experimental data. This requires modifications in the dynamics of the turbulent flow and is under further study. Figure 3 compares the predictions of the two pdf models to the data for the species correlation $\overline{c'c'}$. The error in the mean profiles has been corrected by normalizing the results by the width of the mean species profile. The results for $\overline{c'c'}$ using the "typical eddy" pdf model are in better agreement with the data than the results obtained by neglecting the higher-order scalar correlations. The results demonstrate the importance of modeling these correlations in the calculations.

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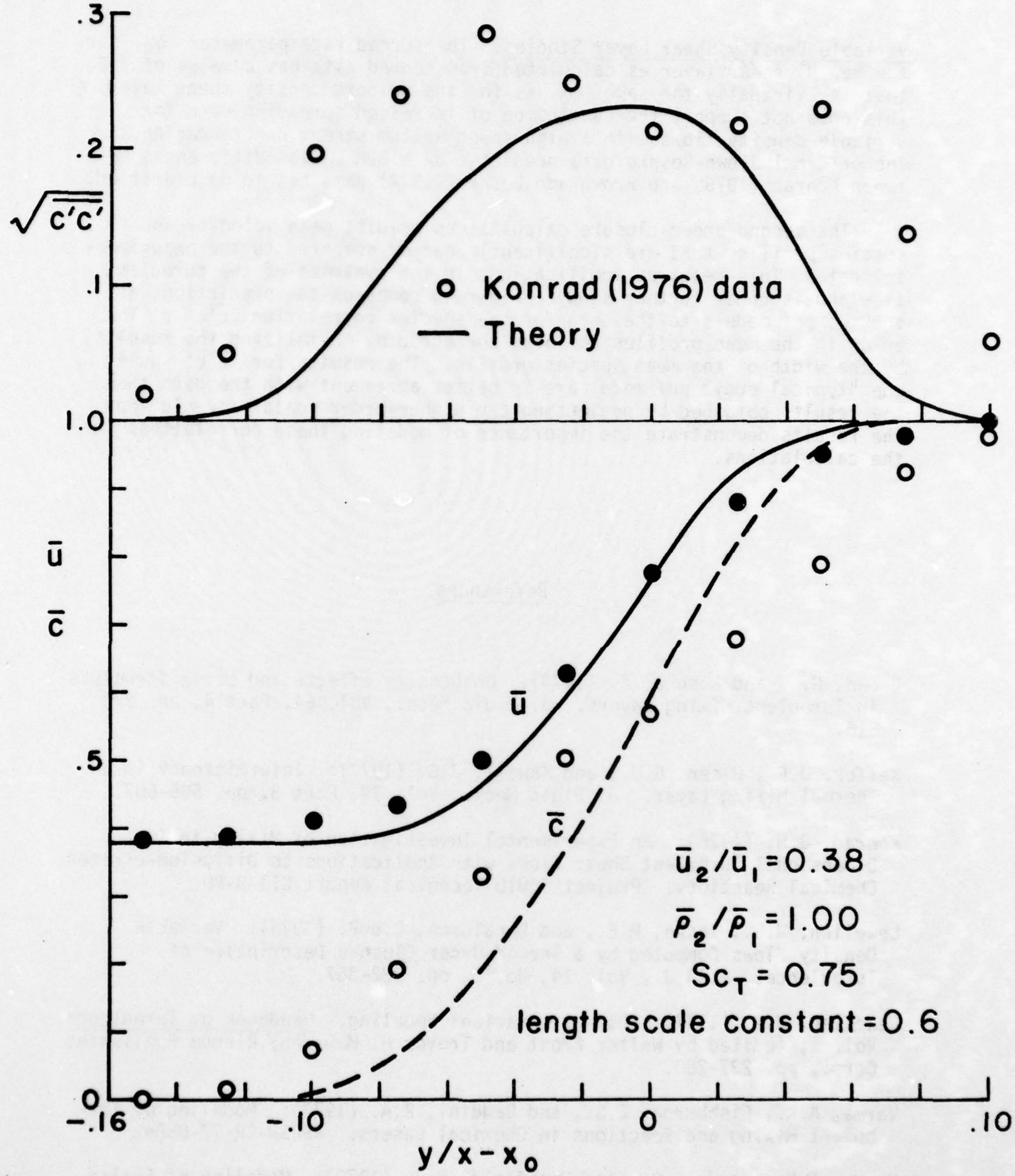

Figure 1. Mean velocity, mean species, and species correlation profiles in uniform density mixing layer.

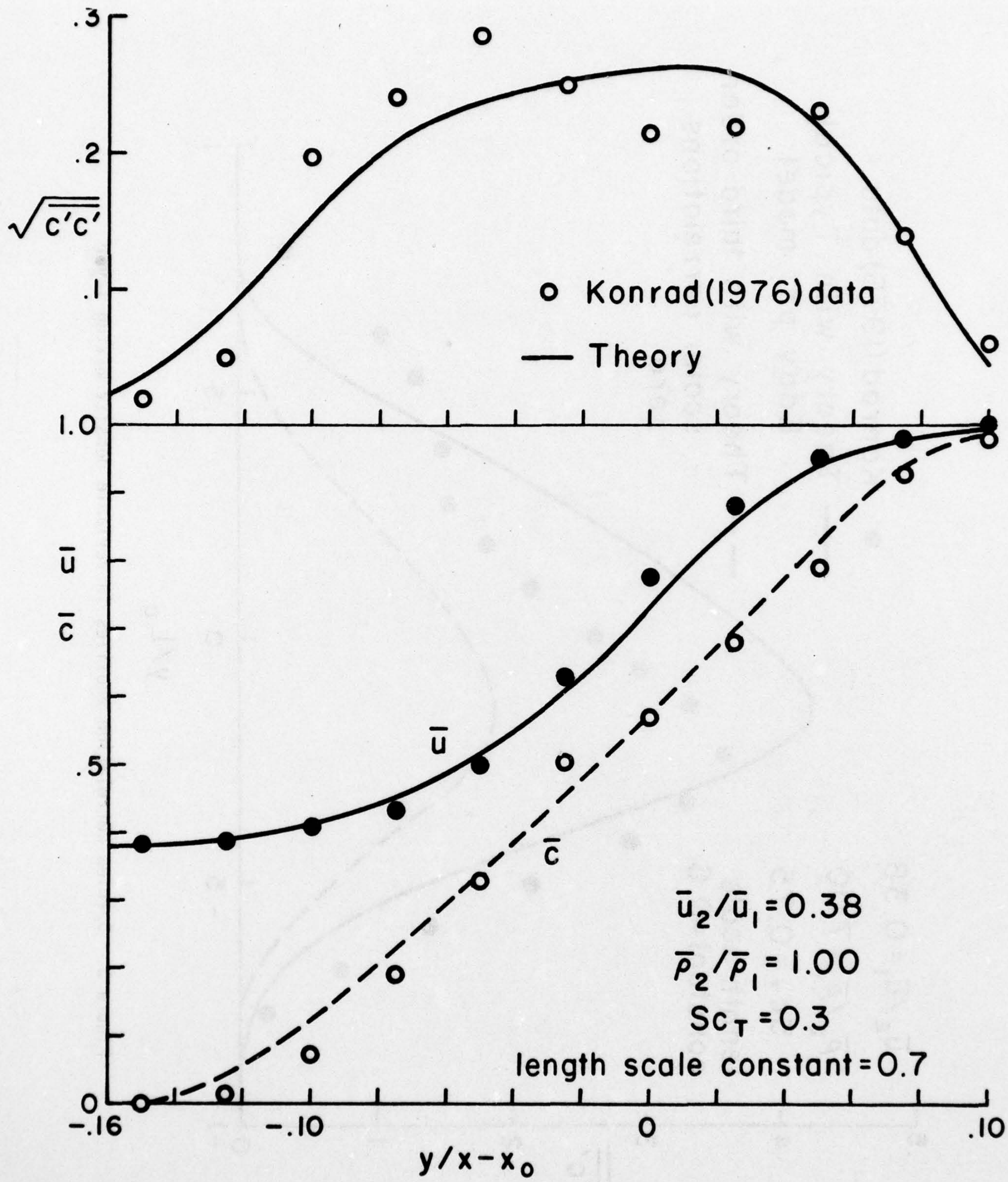

Figure 2. Mean velocity, mean species, and species correlation profiles in uniform density mixing layer with increased length scale constant and decreased turbulent Schmidt number.

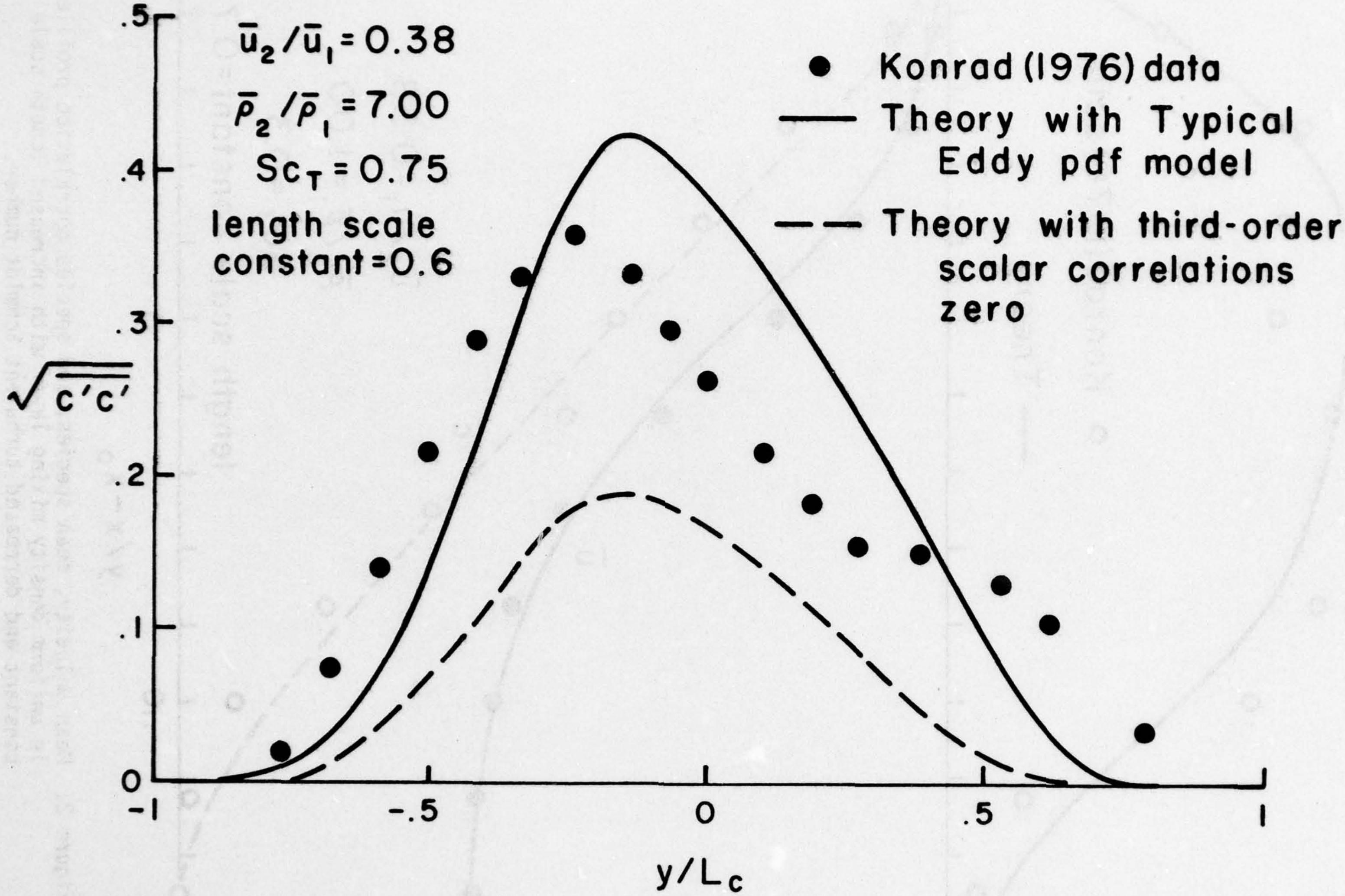

Figure 3. Species correlation profiles in variable density mixing layer.

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Reports of progress during the past six months on the 24 research programs comprising Project SQUID are presented. The research programs fall into the areas of Aerodynamics and Turbomachinery, Combustion and Chemical Kinetics, Measurements and Turbulence. Project SQUID is a cooperative program of basic research related to jet propulsion. It is administered by Purdue University and sponsored by the Office of Naval Research.

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